EbNaut Coherent BPSK

A UT synchronous coherent BPSK mode for use at VLF and low LF enabling communications close to the channel capacity.

The mode uses low rate long constraint length terminated convolutional codes cascaded with an outer error detection code. Encoded symbols are sent UT synchronously with transmit and receive frequencies locked to an atomic standard. Decoding is performed by a soft-decision Viterbi decoder which employs the Soong-Huang serial tree trellis list decoding algorithm. The outer code selects the correct solution from the Viterbi output list. Constraint lengths up to 25 are used, with list sizes up to 200,000.

The long duration phase-stable paths which occur at VLF can be exploited to send messages within 1 dB of the theoretical limit. EbNaut has been used to achieve the first transatlantic amateur communication below 9kHz.

Except in the vicinity of the transmitter, the signal is invisible on a spectrogram. Consequently, transmissions must be announced in advance and the receiver must know the frequency and start time, and which code setting and symbol period to expect.

Measured performance at various levels of E_b/N_0 for the rate 1/16 constraint length 25 code, with list size 50,000.

Message length	E_b/N_0	Success rate
25 characters	-0.5 dB	85 %
	-1.0 dB	63 %
12 characters	-0.5 dB	87 %
	-1.0 dB	70 %
5 characters	-0.5 dB	84 %
	-1.0 dB	74 %

Software is available for Linux and Windows. It it written in C and is open source under the BSD 2-clause license.

Contents

Background

Developments in error correction techniques have led to the common use of turbo codes and low density parity check codes which can both perform usefully at E_b/N_0 below -0.5dB. This performance is only achieved with large block sizes (of order several thousand bits). For block sizes typical of short amateur radio exchanges (a couple of hundred bits), they are not effective.

Recent experiments show that convolutional codes using long constraint lengths, when combined with list decoding, can produce a useful success rate on short messages down to E_b/N_0 of -1.0 dB. Successful decodes can be obtained with over 60% probability at this signal level using a code complexity which is within reach of modern PCs. For general communications, a 40% message failure rate would be considered very bad. A network connection such as WiFi suffers badly with only a couple of percent of lost packets. But a radio amateur attempting communication at the limits of a workable signal will expect to have to make a couple of attempts before success. In this context a 60% success rate is quite acceptable and with only a 0.5 dB increase in signal strength, the success rate approaches 90%.

The mode described in these notes emerged from a series of experiments at VLF by Markus Vester DF6NM, Dex McIntyre W4DEX, and others. At VLF, where signals are at audio frequencies, it is quite easy to use coherent signalling in which the carrier frequency and phase are stabilised with reference to a pulse-per-second signal from a low cost GPS. Little or no specialised hardware is required for this - most of the work is done by a PC soundcard and readily available software.

Radio amateurs have access to a large number of digital communication modes, many of which will operate with weak signals and employ a modest amount of forward error correction. However, they all to some extent have to compromise sensitivity in order to cope with frequency offset and drift, rapid propagation changes and various types of fading, multi-path distortion, and interference from other signals. The opportunity to use coherent signalling, and the particular nature of VLF propagation, enables us to avoid anything which compromises sensitivity. We use the simplest and most efficient modulation - coherent BPSK, and combine this with the strongest forward error correction that is capable of being decoded on a modern PC.

VLF Operation

Signals at VLF propagate very well. Ground and ionosphere are low loss reflectors and signals are effectively trapped in a cavity formed between the Earth and the D or E regions of the ionosphere. Transmitted power expands cylindrically into this cavity to produce a received power density roughly inversely proportional to range. On top of that, the attenuation due to losses is relatively low, ranging from 0.5 dB to 8 dB per 1000km, depending on frequency, time of day, land or sea path, and direction relative to the Earth's magnetic field. Paths are generally stable and repeatable, often with little or only slow fading and signals can be received with a steady phase sometimes for hours at a time.

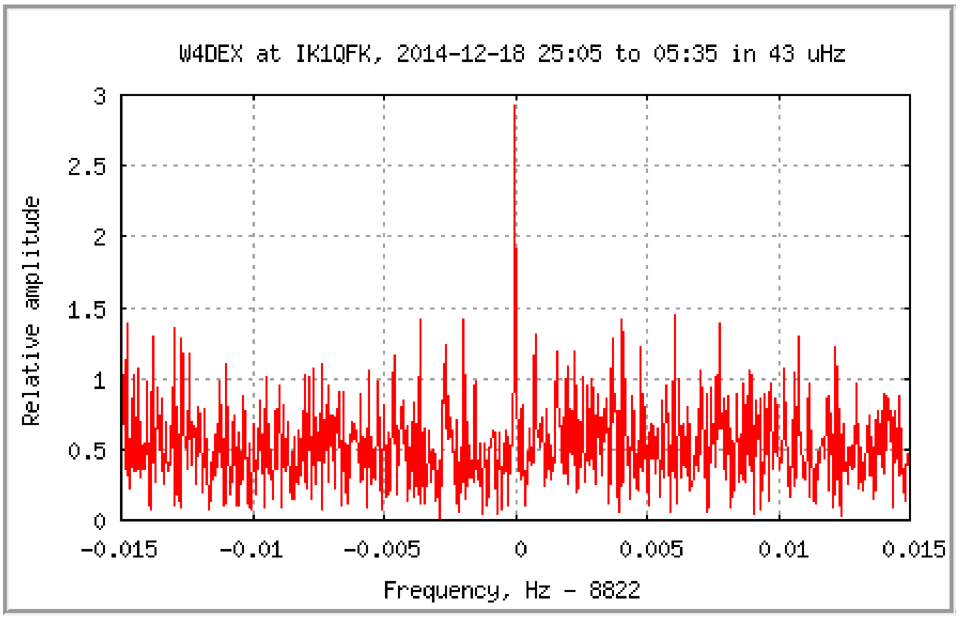
While the propagation at VLF is rather attractive for long distance communications, the band presents considerable difficulties for both transmitter and receiver. The long wavelength relative to practical antenna sizes means that only very small radiated powers can be expected. A small VLF antenna may produce an ERP of 5 to 20uW, a large amateur fixed installation can achieve a few hundred uW, and up to a few mW may be radiated with kite antennas. The receiver is faced with very high levels of local interference, predominantly harmonics of the power line frequency and noise from digital electronics. The natural background at VLF is also very high because electrical discharges from storms radiate strong signals which propagate worldwide.

Amateurs have recently discovered that these difficulties are far from insurmountable. Reception techniques which minimise interference pick-up, powerful digital signal processing on modern PCs, and the use of extremely narrow bandwidths made possible by the stable propagation and GPS timing, open up the band for practical use. It is not too difficult for a 10uW ERP signal to be detected at 1000km range and with appropriate modulation and error correction coding, messages can be sent.

Weak Signals

The VLF band is the perfect playground for the weak signal enthusiast thanks to the ability to use long duration coherent detection. The fact that even a few milliwatts of ERP counts as a high power transmission ensures that all signals are 'weak' compared to operations at any other band. A VLF signal which is 40 dB below noise in an audio bandwidth would be described as 'a spectacularly strong signal' and almost all amateur signals are immersed a further 20 or 30 dB deeper still in the VLF background. Signal strengths in receiving antennas can be given by counting electrons - sometimes in single figures.

Much has been achieved simply through carrier detections in very narrow bandwidths rather than message reception. Typically the distant signal appears as a sharp line in the receiver's output spectrum and its origin is confirmed by a shift of frequency. An example on the right shows the small but significant peak of a 150uW carrier detected at a record distance of 7173 km.



Messages are also sent, usually using some form of slow Morse with dot periods of 600 seconds or more. This can be read easily by eye on a spectrogram but makes poor use of the channel capacity. Much better performance is obtained using MFSK or BPSK. Markus Vester DF6NM has experimented with MFSK at VLF with good results, including a 2-way exchange of MFSK-37 messages with Lubomir Bobalik OK2BVG. Considering the phase stability of VLF paths and the need to fight for every available dB, there really is no excuse not to gain 3dB by the use of coherent signalling and both coherent MFSK and BPSK are theoretically capable of making the best possible use of the very small signal/noise ratios.

Messages at the Limit

A carrier detection conveys one bit of information - it is an un-encoded single bit message using amplitude shift keying. VLF signals, despite their depths in the noise, can do much better than that. The example above of carrier from W4DEX received in Italy could have carried a 42 bit message (say, 7 characters), with over 70% chance of being successfully decoded. There is a fundamental limit to the amount of information which can be reliably conveyed by any signal. Oddly at first sight, this is determined by how many spheres you can cram into a volume of a hyper-dimensional space. This is the sphere packing limit (see Appendix) which converges to the well known Shannon limit as message lengths become longer and longer.

The challenge for any combination of modulation and encoding, is to approach this limit as closely as possible in order to convey the most information using the available signal/noise ratio. The universally used comparative measure of performance is E_b/N_0, a dimensionless ratio which allows all different modulation and coding schemes to be compared on an equal footing regardless of whether they are sending megabits per second for a TV signal, or a few bits per hour at VLF. The limit is -1.59 dB and a message received at close to this level is using nearly 100% of the channel capacity. A signal received at E_b/N_0 of +5dB is using less than 25% of the capacity of the channel.

The article Signal/noise ratio of digital amateur modes by Pieter-Tjerk de Boer PA3FWM, tabulates the typical E_b/N_0 of some amateur modes and includes a clear explanation of E_b/N_0. Most communication links have to sacrifice some capacity in order to be robust with respect to fading, frequency offsets, phase changes, multi-path interference, and so on. A long distance path at VLF suffers few of these problems and amateur stations with GPS timing can operate closer to the capacity limit than at any other band.

The challenge for the operator is to estimate how many bits can be sent, given some VLF propagation window and signal strength. A good guess can produce a result at 80% or more of the channel capacity. An over-optimistic attempt will produce no result at all. This requires some skill in the art of evaluating the conditions and propagation, typically by doing some carrier tests beforehand. The Signal Calculator page assists with this. You plug in some carrier measurements and then experiment with the different codings, symbol periods and message lengths, to choose some suitable settings.

A nice feature of this game of pushing towards the channel capacity limit is that low power short range stations can compete on equal terms with stations running high power from large antennas. Instead of striving for a higher S/N ratio by using more power or more sensitive receivers, you are trying to make the most of whatever S/N ratio you happen to have.

Development

Experiments are ongoing to implement a message prefix to enable un-announced transmissions. The message prefix indicates the code setting and length of the message. Subject to certain restrictions on symbol period, carrier frequency and start times, the prefix allows a receiver/decoder to monitor a band for EbNaut messages.