Long Haul VLF/LF/HF Data Networks

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***Abstract*—the need for long haul, worldwide radio data networks comes even at a time when much of the modern telecommunications networks have been integrated with the internet. The level of decentralization in wireless long haul radio networks allows for high degrees of reliability and redundancy much beyond is currently possible using permanent wired and wireless packet switched data network infrastructure like the Internet and cellular networks. In the case of a large scale disaster that has the capability to bring down even well-established permanent telecommunications networks, it's possible that the closest working infrastructure in such a disaster could be miles away from ground zero. Using the open air and ionospheric reflection propagation a medium, robust wireless data links can be established over hundreds or even thousands of miles.**

I. Introduction

The dawn of wireless radio telecommunications came when the first amateur radio operators started building their own radio equipment after the discoveries and pioneering efforts of people like Guglielmo Marconi and Nikola Tesla. The oldest and most reliable form of digital radio communication, Morse code, is still in wide use today by amateur radio operators. Even while Morse Code telegraphy is considered by many the most reliable wireless communication scheme, it could not meet the need for faster wireless data links.[1] The next step of evolution came when Radioteletype (RTTY) saw an explosion of growth in the 1930s and subsequently, World War II. This was the first truly digital (binary) method of communications. RTTY is perhaps the most widely used method for low frequency commercial and military communications around the world even today. Of course, this still did not meet the need for high speed robust wireless data networks. The innovations of more than a century of pioneering research and development in the wireless telecommunications industry has led to modes of communication that closely match our current needs for long haul data networks that provide as much reliability as is humanly possible. There are many different protocols for getting data where it needs to go; some of them open protocols free for everyone to use, and others proprietary requiring a license to use. Some of them are encrypted to obfuscate the meaning of the message being transmitted while others are in the clear for everyone to receive. Today, the government, the military, commercial entities, and amateur radio operators all have their own methods of establishing communications in an emergency situation. This is an attempt to document a number of these methods based upon their reach and the underlying communications fundamentals that drive them.

II. Digital communications modulation

A. *Morse Code (Continuous Wave)*

Morse code is the simplest, oldest, and most fundamental method of radio communication in the world. Morse code consists of a series of two carrier modulated pulses or tones (as heard at the receiver) of different lengths. The shorter tone is the dit, while the longer tone is the dah. Using an internationally standard alphabet, International Morse Code, alphanumeric messages can be sent and received by both man and machine using this mode of communications. Its bandwidth needs are fundamental in that the bandwidth occupied by a Continuous Wave signal is that of the frequency of the carrier. Its speed or data rate is relative to the speed at which the two tones are sent in the time domain.

B. *Radioteletype (RTTY) or Frequency Shift Keying (FSK)*

Radioteletype is an early form of digital communication that uses a 5 bit code, Baudot, modulated through means of Frequency Shift Keying (FSK), or, changing the frequency of a carrier wave between two different states (0, and 1). RTTY is defined by the speed at which the carrier is shifted (symbol rate), and how much the frequency of the carrier is shifted. The most common and recognizable form of RTTY is 45.45 Baud, 170Hz shift. FSK RTTY is also widely used in naval communications through the use of high power VLF (because of its ability to penetrate salt water) and HF transmissions.

C. *Phase Shift Keying (PSK)*

Phase Shift Keying is a more modern method of keying digital information that is more spectrally efficient, meaning it does not require as much bandwidth as its FSK counterpart to achieve the same data rates. Phase Shift

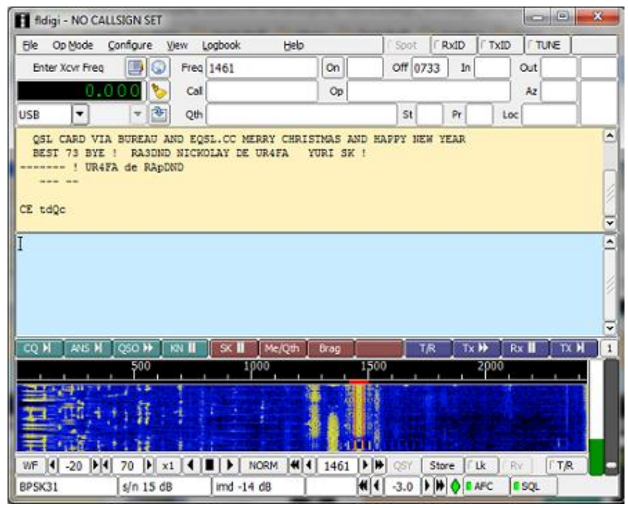
Keying is achieved by shifting the phase of a carrier with a variable length coding system (varicode) to key digital information. [3] If it's keying data in a binary fashion, it's BPSK (Binary Phase Shift Keying), having only two states that can be modulated, 0 and 1. PSK can also be adapted to convey more information per symbol using higher order modulation schemes such as QPSK (Quadrature Phase Shift Keying). QPSK is Phase Shift Keying coupled with Amplitude Modulation to provide more bits per symbol transmitted. [2] The basic QPSK (also called 4-QAM) has four different states, thus, the ability to encode two bits per symbol. Higher order schemes allow for even higher rates. The majority of air interfaces across all breadths of wireless telecommunications have adopted Phase Shift Keying and QPSK/QAM as modulation schemes to transmit digital information due to its high level of spectral efficiency. While PSK/QAM may be the fastest way to key digital information, it is more susceptible to interference caused by multipath propagation and signal attenuation/distortion.

III. AMATEUR RADIO DIGITAL EMCOMM

Amateur Radio is truly unique in its ability to set up and establish emergency communications in the field in the absence or failure of permanent commercial or even governmentally sponsored temporary emergency communications networks because of its open platform and interoperability between many different people, many different agencies, and many different countries due to its standard set of communications platforms and its volunteer operator reach. Amateur Radio operators are active every day on their respective licensed portions of radio spectrum around the world testing and designing new methods of communication. There are two large systems of digital communications currently in use by amateur radio operators around the world today. One is NBEMS (an open digital EMCOMM platform) and the other is Winlink (a somewhat open radiomail platform for sending Email over radio links). In addition, Packet Radio still sees widespread use and has been adapted into a new system called APRS, which is essentially a VHF (or even HF) mesh radio network.

A. NBEMS

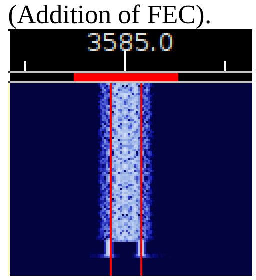
NBEMS is the Narrow Band Emergency Messaging System. NBEMS is the culmination of the work of hundreds of amateur radio operators around the world to create a digital emergency communications platform that all amateur radio operators (and even non-amateurs) from around the world can use for free under GPL licensing to use their general purpose PCs and sound cards as digital modems capable of interfacing with many different combinations of hardware. [4] The ability to interface with nearly any combination of hardware allows NBEMS to be deployed quickly on any set of spectrum available to use. NBEMS is widely used on the High Frequency amateur radio bands where ionospheric propagation allows for a wide audience and on VHF/UHF where high speeds are possible due to the higher availability of bandwidth and lower atmospheric noise conditions. The most popular implementation of NBEMS is in the FLDigi software suite created by David Freese, W1HKJ, and contributed to by others. [5] FLDigi acts as the digital modem to encode and decode digital signals using a computer sound card. FLDigi provides many different modes all with different characteristics. All of the modes follow a Frequency Shift, Phase Shift, or Amplitude Shift (CW) Keying method to modulate digital data. FLDigi provides the ability to have a keyboard to keyboard chat with someone across the country or across the world with a mode of choice, or, it provides the data link support for protocols such as FLMSG and FLAMP that allow messages such as ICS forms, Radiograms, or even raw data files to be sent with proper formatting, data compression, and/or Forward Error Correction to the user(s) on the other end with automatic checksum calculations and bad section requests for completing blocks of missing data.



Modes

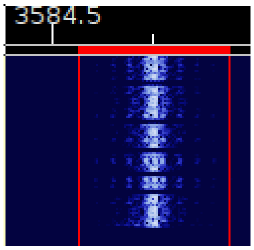
A. PSK (most popular)

Available in flavors of 31Hz to 1000Hz, with the bandwidth corresponding to the baud rate. Also includes implementation of QPSK and PSK-R (Addition of FEC).



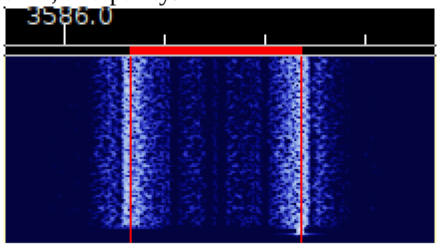
B. CW (Morse Code)

Automated transmission and reception of Morse code.



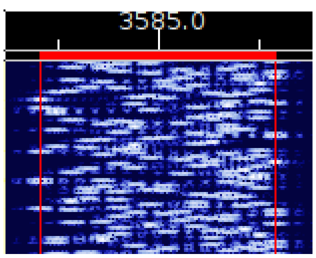
C. *FSK (RTTY)*

Custom configurations - variable baud rate, encoding, shift, and parity.



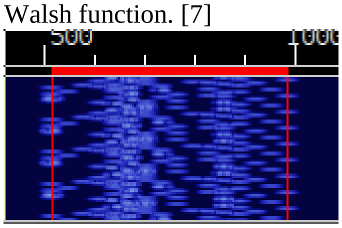
D. *MFSK*

A variation of FSK that uses multiple frequencies (tones) to provide an M-ary orthogonal signaling scheme, meaning, each tone from the alphabet provides $\log_2 M$ data bits. There are many different forms of MFSK, but the most common involve using 16-32 tones in a 500Hz or 1 KHz wide channel. [6]



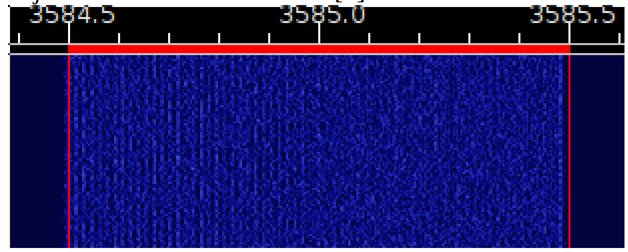
E. *Olivia/Contestia*

Olivia/Contestia is a variation of MFSK that adds heavy forward error correction through the use of the Walsh function. [7]



F. *MT-63*

Involves the use of 64 Orthogonal Frequency Division Multiplexed (OFDM) carriers spaced 15.625Hz apart (1 KHz channel width) which are then phase shift keyed. It utilizes 64 bit Walsh function FEC with an interleaver to spread each character (byte) across 32 or 64 symbols. Due to the level of FEC, this mode is highly resistant to common sources on interference such as static crashes and fading (short loss of entire channel), and adjacent channel interference. [7]



(Images thanks David Freese, W1HKJ)

B. *Winlink*

Winlink is an HF radiomail protocol that enables the transmission and reception of emails between other amateur radio operators and the internet through the use of email gateways that are stationed around the globe. [9] Winlink is different from NBEMS in that the data it carriers is email based, highly automated (gateway stations are completely automated not requiring an operator) with ALE (Automated Link Establishment), and sees the use of both proprietary and open air interfaces. Winlink employs two primary methods of email communication. One is peer to peer based, allowing two stations to exchange emails without the need of an intermediate gateway. The other involves connecting to a network trusted gateway station that is tuned to an established frequency listening for link establishment requests. Once a link has been established, the gateway then fetches emails that need to be sent to the user from a core network that is mixed with both amateur to amateur messages, and email messages that have been gated from the Internet. To prevent spam email from overwhelming the capacity of the network, each user must whitelist addresses for which they can accept emails from. The gateway will also give the user the opportunity to send emails through the gateway which are to be forwarded to the core network and on to another amateur operator or to an email address on the public internet. Winlink is used very frequently in the marine HF radio bands as a way for mariners at sea to establish an email connection (sometimes in an emergency) with the internet on shore, or with other users at sea. The system provides an alternative to expensive and sometimes highly unreliable satellite communications systems.

Winlink sees the use of specialized commercial data transmission equipment that pushes the throughput capabilities of an HF radio channel to near its limit. The attraction to Winlink is its speed. Many Winlink gateway stations and user stations are equipped with commercially designed PACTOR enabled modems that interface between a PC and an HF radio. PACTOR is a data transmission mode that uses a combination of a modulation scheme, and Time Division Duplex to add ARQ (or Automatic Repeat Request) functionality to the channel. The latest version of PACTOR, PACTOR-IV Dragon is a mode developed by SCS, GmbH. that provides the highest level of two way data communications throughput than anything else on the market. [10]

PACTOR – IV Dragon

- 2.4KHz Channel Width
- 10 speed levels chosen automatically based upon conditions. (DQPSK (with spreading), BPSK, QPSK, or higher order QAM)
- Backwards compatibility with all previous versions of PACTOR.
- Peak throughput of 5.5kbps (without compression) or 10.5kbps (PMC compression)
- Can maintain a connection up to a -20dB Signal-to-Noise ratio.
- Very fast ARQ
- Iterative adaptive equalizer for speed levels 5-10, RAKE receiver with spread speed levels (2-4).

Winlink has seen seasoned use in areas of natural disaster such as in the aftermath of Hurricane Katrina, where commercial telecommunications networks were simply unavailable or highly unreliable for weeks. It has also been used in last resort distress situations by vessels at sea that have needed immediate help and were unable to establish communications through maritime SSB telephony channels, or satellite systems.

C. Automated Packet Reporting System – APRS

APRS evolved from an old network of BBS (Bulletin Board System) packet radio stations that were popular in the late 1980s and 1990s as an amateur radio network similar to that of the state of the internet during its time. The most popular and widespread form of APRS uses an air interface called AX.25. AX.25 is a data link layer protocol that was based upon the X.25 packet switched wide area network protocol and repurposed for amateur radio use. Each AX.25 message (or packet) identifies the message sender (plus SSID which acts as the port), destination, a path (to determine how the message is to get to its destination), and a payload of variable length. [11]

The majority of the APRS network operates on the VHF frequency of 144.39MHz at 1200 baud, while 300 baud is possible on HF, and 9600 baud on UHF. VHF APRS employs Time Division Multiple Access (TDMA) since there is only one channel in this network. APRS is fundamentally a mesh radio network because of its widespread adoption and coverage across large areas (in this case, across the U.S.). Coverage is determined by equipment that has been set up by amateurs that have volunteered their equipment for the task.

The majority of APRS traffic is position information and short text messages transmitted by mobile or portable ground stations. Many APRS transceivers are equipped with GPS receivers to determine their position, which is then transmitted to the network to be forwarded on. The core of the network involves hundreds and thousands of “digipeaters” that are located all over the world. The function of these digipeaters is to repeat the packets that it receives from other stations (if the packet’s path, or TTL, has not expired). Some of these digipeaters are internet enabled and can then gate the network traffic that they receive to an internet network that is open for everyone to monitor over the internet through web portals and telnet connections. They can also act as a gate from the internet to radio. For example, if user A in California wants to send a message to user B in Pennsylvania and both users have established their presence on the network via an Internet gateway (usually through a beacon packet), then user A can send the message over radio to the nearest iGate, which will then send the message over the internet to the iGate in Pennsylvania which will transmit the message over radio the user B in Pennsylvania. Message deliveries are confirmed by the receiving station by sending an “ack” or acknowledgment packet back to the sender.

In theory, it is possible for a message to be relayed all the way across the country using APRS without the need for the Internet. If a packet was given an extremely long Time to Live (or highly specific path), it is possible for the packet to jump from digipeater to digipeater over VHF until it reaches its destination. Of course, doing so would probably clog up the entire network because there is a very limited amount of throughput and it would be possible for packets to jump around the network without any real direction until the Time to Live of the packet expires.

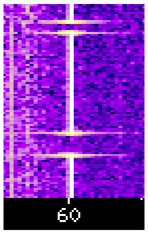
IV. Government/Military

While amateur radio operators have provided multiple systems for use in long haul emergency data communications, governments and militaries around the world have undoubtedly had a need to have communications systems of their own for secrecy and exclusivity purposes. While the specifics of many military grade communication networks remains secret, a good bit of information is known about the networks that drive long distance military communications, at least the one to many broadcast systems.

A. Time Signals (WWVB)

High precision time synchronization has largely been replaced by GPS due to its higher reliability, especially during daylight hours; however, many nations around the world still provide time signals to their citizens for synchronizing clocks and for highly stable frequency references. In the U.S., WWVB in Fort Collins, CO provides a time signal for the 48 contiguous states on a frequency of 60 KHz.

WWVB employs two methods of data modulation. The simple modulation scheme employs trinary Amplitude Modulation. At the beginning of every second, the transmitter’s power is reduced (AM) depending on the state that needs transmitted. For example, to transmit a marker, the power is reduced for 0.8s, for a binary 1 0.5s, and for a binary 0 0.2s. The duration of the second, the transmitter is restored to full power. In late 2012, an independent time code was added to WWVB’s transmission by phase modulating (BPSK) the carrier. The addition of the phase shift keyed time code allows more sophisticated receivers to distinguish the binary code in cases of low signal strength, high noise floors, and interference from other time code signals (like MSF from the U.K. also on the same frequency). [12]



(MSF)

B. VLF FSK Broadcasts

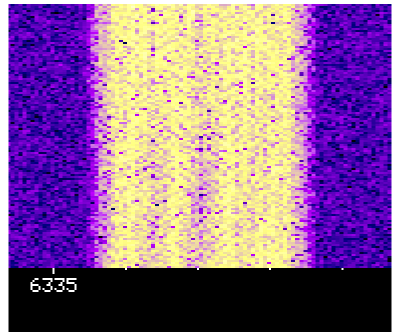
NATO operates a system of very powerful and very low frequency radio transmission stations for the purpose of issuing orders to its strategic forces stationed around the globe. Given the breadth of their network (at least one station placed to cover every corner of the globe), this is one of the only terrestrial data communications networks that covers the globe. While the frequencies and transmission locations of all of these stations are not completely known, there are a few notable ones. The U.S. Navy operates a VLF transmitter in Cutler, Maine to provide one way communications to its strategic submarine forces on 24 KHz.

Due to the frequency at which these transmissions are broadcast, the size of the antenna and the power needed to broadcast a strong signal makes it extremely difficult for the data link to be two way. VLF Cutler employs a transmitter with an output power of 1.8 Megawatts and an antenna array consisting of 13 tall support towers which suspend an umbrella antenna (functioning as a top loaded monopole). The power and size of the array makes this one of the strongest VLF signals in the world. VLF Cutler transmits a 200 baud Frequency Shift Keyed encrypted teletype signal that can be received over a good portion of the northern hemisphere and up to a few hundred feet under water. Due to its slow data rate, it is usually used to command submarines to surface to establish two way communications on HF (or via Satellite), or to issue an Emergency Action Message (authorize the use of nuclear weapons). [13][14]

C. STANAG-4285

STANAG-4285 is a one to many (broadcast) digital transmission mode used by NATO forces over HF that provides much higher data rates compared to FSK and added bonuses like advanced forward error correction. It provides many different speed settings (up to 2400bps); however, the most common is 600bps with long block interleaving. S-4285 employs Time-division multiplexing, allowing for messages to be sent to different recipients simultaneously using different timeslots. Similar to the FSK systems, S-4285 is usually used to order receiving stations to establish two way communications through Link 11 or through Satellite communications systems, or to issue critical orders. [15]

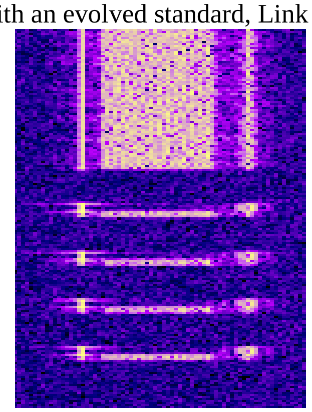
Many STANAG-4285 transmission sites employ very large, high gain HF broadcast antennas and high power transmitters to create a network that, with transmitters placed strategically, can cover the entire globe even with uncertain propagation conditions.



(STANAG-4285)

D. MIL-STD-188-110B (TADIL, Link 11)

Link 11 is an encrypted half duplex radio link system employed by many NATO nations to provide sequential data exchanges between its airborne, land-based, and sea-based tactical data systems over HF. It can provide robust data communications between military forces at up to 9600bps on HF through ARQ and heavy use of FEC. It will be replaced with an evolved standard, Link 22. [16]



(TADIL)

(Images created using the Wideband SDR WebSDR project)

V. Conclusion

While this has been by no means an examination of all of the digital communications modes and methods used by users of the VLF/LF/HF radio bands around the world, I have provided a short summary of some of the most vital communications systems that the world relies upon, even when most of the global telecommunications traffic has moved to high frequency wireless radio networks (cellular networks) and the wired internet. The combined level of centralization and decentralization across the entire HF spectrum by its users all but guarantees that digital communications (albeit maybe not very fast) can be established if needed when permanent infrastructure is not functioning. The importance of maintaining long haul data networks like the ones I have mentioned is no less important even now when wireless cellular networks have gotten larger and have adopted a large user base because the infrastructure is too centralized and can be overloaded or brought offline in the wake of a disaster.

Acknowledgment

I would like to express my gratitude towards everyone who has led me to where I am at in my life, working towards a fulfilling career of my own. I would like to thank Dr. Tipper for teaching this wonderful course and offering his insights into wireless telecommunications. Finally, I would like to thank everyone in the amateur radio community for teaching me so much about radio and helping me discover my passion for it.

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