AX.25 + FEC = FX.25

John Langner, WB2OSZ, December 2019

What can you do if your radio signal isn't quite strong enough to get through reliably? Move to higher ground? Get a better antenna? More power? Send data very very slowly with narrow bandwidth?

Sometimes those are not options. Another way to improve communication reliability is to add redundant information so the message will still get through even if small parts are missing.

In the data communications world, adding additional information, so the receiving end can fix up errors, is known as Forward Error Correction (FEC). This is very common. It is used in all sorts of radio communication, QR codes, DSL, and disk drives. It is even used with CD's and DVD's to work around errors caused by scratches.

AX.25

The AX.25 frame, used by APRS and Amateur Packet Radio, is not very tolerant of low quality radio links. A 16 bit "Frame Check Sequence" (FCS) is computed from the earlier parts. The receiving end recomputes the FCS and discards the frame if there is a mismatch.

"Flag" pattern	Addresses	Control	Information	Frame Check Sequence	"Flag" pattern

All it takes is a single bad bit to ruin the entire frame. Traditional connected mode packet has automatic acknowledgment of received frames and requests to resend any that are missing. APRS does not use this feature so the information is just gone and nobody knows.

FX.25

Back on 2006, the Stensat Group came up with a clever way to add Forward Error Correction to AX.25 while maintaining complete backward compatibility with existing equipment. It starts with carefully chosen 64 bit patterns to identify the format of the data to follow.

8 bytes	32 to 239 bytes	16, 32, or 64 bytes
Correlation Tag	Data (Normal AX.25 Frame)	Parity Check

Depending on the Correlation Tag, certain numbers of bytes are gathered for the "data" and "check" parts. The Reed-Solomon algorithm is used to fix any errors. The number of bytes that can be repaired is one half the number of check bytes.

Tag Number	Correlation Tag Value	Data Bytes	Check Bytes	Number of Defective Bytes that can be repaired.
0x01	0xB74DB7DF8A532F3E	239	16	8
0x02	0x26FF60A600CC8FDE	128	16	8
0x03	0xC7DC0508F3D9B09	64	16	8
0x04	0x8F056EB4369660EE	32	16	8
0x05	0x6E260B1AC5835FAE	223	32	16
0x06	0xFF94DC634F1CFF4E	128	32	16
0x07	0x1EB7B9CDBC09C00E	64	32	16
0x08	0xDBF869BD2DBB1776	32	32	16
0x09	0x3ADB0C13DEAE2836	191	64	32
0x0A	0xAB69DB6A543188D6	128	64	32
0x0B	0x4A4ABEC4A724B796	64	64	32

The sender can choose an appropriate correlation tag depending on amount of space required for the AX.25 frame and the desired strength of error correction.

FX.25 has been used for several Amateur Radio Satellites but never gained any acceptance outside of that little niche. Now that FX.25 has been integrated into a general purpose TNC, many new possibilities are now open.

We will be performing some experiments to see how well it actually works.

Bit Error Rate

"Bit Error Rate" (BER) is a common measurement of how well a digital communication channel performs. It is simply defined as the number of incorrect bits divided by the total number of bits. Errors can be caused by many factors such as natural random noise, man-made interference, multi-path, fading, low quality modems, incorrect adjustments (e.g. transmit audio level), and distortion added by the radios (e.g. limited bandwidth, pre-emphasis & de-emphasis).

It is easy to compute the impact of different bit error rates. If the probability of any bit getting corrupted is B then the probability of it getting through correctly is (1 - B). The probability of N bits getting though correctly is $(1\text{-}B)^N$. Let's compute the probability of an 80 byte (640 bit) frame getting through with different error rates.

Bit Error Rate B	Probability of success. $(1 - B)^{640}$
0	1.000
10^{-5}	0.994
10^{-4}	0.938
10^{-3}	0.527
10^{-2}	0.002

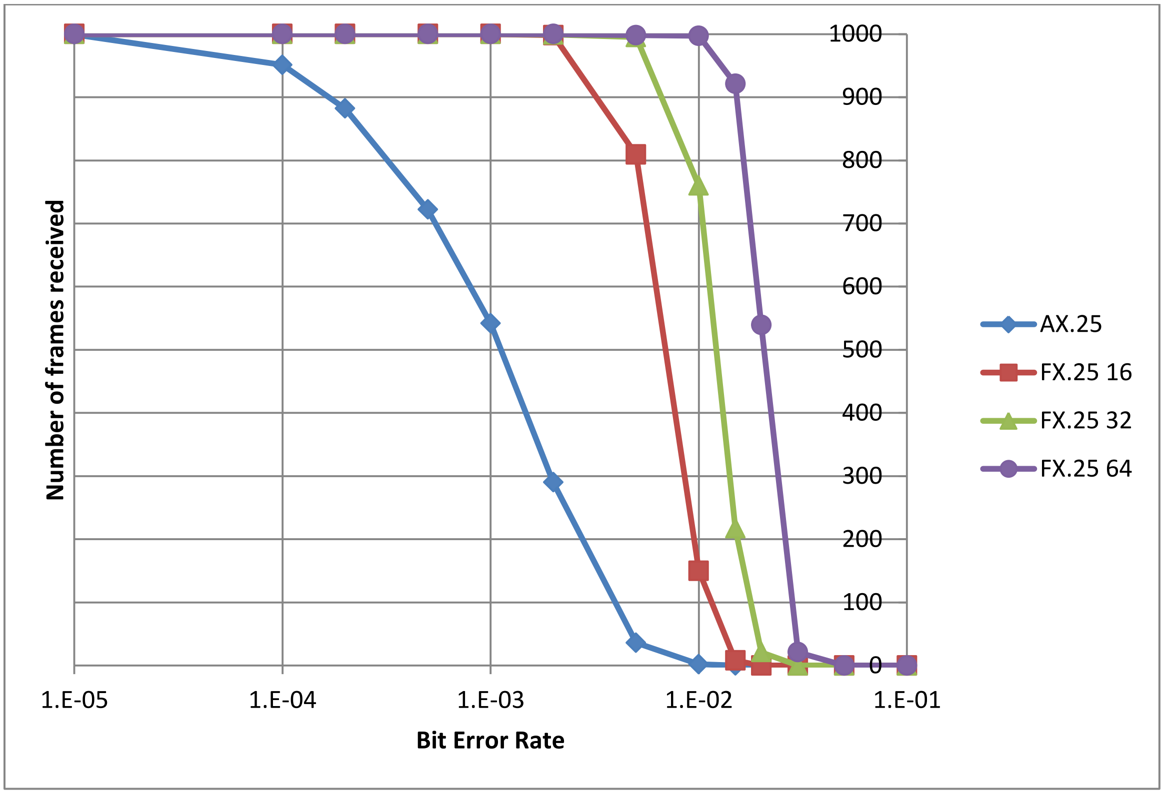
Now we will try it experimentally. Generate a thousand APRS packets and measure how many are received. The receiving end has an option to introduce a given Bit Error Rate, after the demodulator, using a random number generator.

AX.25 success rate vs. BER	
Bit Error Rate	Number received
0	1000
10^{-5}	999
10^{-4}	951
10^{-3}	542
10^{-2}	2

The experimental results are quite similar to the theoretical expectation. Loss of only 1 bit in 1000 (BER = 10^{-3}) causes almost half of the frames to be lost.

FX.25 Improvement for APRS

Now we will do the same thing, using FX.25, again with 1000 frames. The sender has a choice of 16, 32, or 64 check bytes. Once again, we introduce a controlled Bit Error Rate at the receiving end and count the number of frames received correctly.



FX.25 keeps going strong long after regular AX.25 is completely useless.

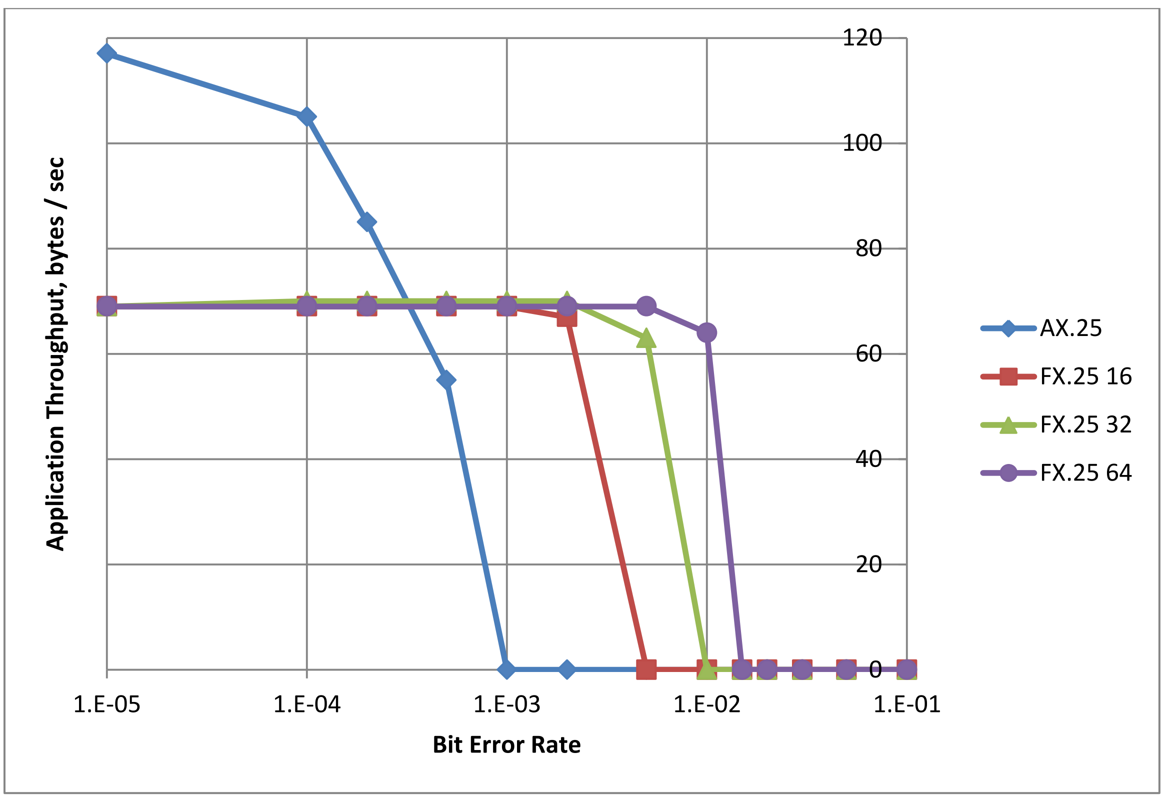
FX.25 Improvement for traditional Packet Radio

Connected mode uses the same AX.25 frames but in a different way. Rather than a broadcast to everyone, it is used as a link between two specific stations. The sending TNC assigns sequence numbers to the information frames. The receiving end acknowledges what has been received and asks for fill-ins of missing pieces.

Connected mode AX.25 packet radio is often used, with applications like Outpost PM and WinLink Express, for emergency communications. Temporary antennas and loss of infrastructure make reliable communications more difficult. Anything that can extend range and improve reliability could have a significant impact on people's lives.

This test uses 100 frames each with 128 information bytes.

The total amount of application data transferred, divided by the elapsed time will give us an effective throughput rate, measured in bytes per second here. As the error rate increases, more retries are required, and the throughput decreases. At some point, it just gives up before reaching the end. We give this a score of 0.



Under good conditions, FX.25 is slower because it has more overhead. When conditions deteriorate, FX.25 show little or no degradation long after AX.25 is completely useless.

One could imagine a system where the FX.25 transmission is enabled or disabled based on the error rate detected on the receiving end. It would not have to be symmetrical. Maximum throughput might be achieved by a low power station transmitting FX.25 and a high power station sending regular AX.25.

FX.25 Quick Start Guide

The "Dire Wolf" software TNC now has FX.25 reception always enabled so you don't need to do anything special. Watching for the special correlation tag sequences adds an insignificant amount of additional overhead when only regular AX.25 is in use.

For transmit, simply specify –X (upper case) on the command line followed by 16, 32, or 64, for the desired number of check bytes. The specific correlation tag will be picked automatically based on the frame size. (Initially there is a single option which applies to all radio channels. Don't be surprised if a later revision allows this to be specified individually for different channels.)

At the time this is being written, the new functionality is available only in the "dev" branch. Not too far in the future, it should be in release 1.6.

Summary

FX.25 has been used for more than a decade with some satellites. Receiving implementations were oriented toward that niche application. Now that FX.25 is easy to use, integrated into a general purpose TNC, many other AX.25 based applications can gain the benefits while retaining complete compatibility with older equipment.

Recommended Reading

Wikipedia

https://en.wikipedia.org/wiki/FX.25_Forward_Error_Correction

FX.25 FEC extension to AX.25

http://www.stensat.org/docs/FX-25_01_06.pdf

Dire Wolf documentation

https://github.com/wb2osz/direwolf/tree/dev/doc

Of particular interest, for better understanding of some of the material in this document:

- A Better APRS Packet Demodulator, part 1, 1200 baud
- AX.25 Throughput: Why is 9600 bps Packet Radio only twice as fast as 1200?

Interoperability Testing

The Dire Wolf TNC comes with a utility called “atest” which allows audio to be read from .wav files rather than the sound device.

Here we try testing with few FX.25 audio recordings that were found on the Internet. Some were in mp3 format and had to be converted to wav file format.

Each received frame has signal quality summary like these:

```
_||||_____
_6444_____
_____77788
```

Each character position corresponds to different demodulator.

|	means regular AX.25, no errors.
_	means nothing received.
digit	is number of bytes corrected for FX.25.

When skewed to the left, the two AFSK tones have similar amplitudes. When skewed to the right, the higher audio tone is considerably weaker, probably because the receiver used de-emphasis and the transmitter did not use pre-emphasis to compensate.

Unprintable characters are displayed in hexadecimal format like this:

<0x0a><0x0a> means two ASCII line feed characters

Additional debug information can be displayed with the “-dx” or more detailed “-dxx” command line option.

ande2_demo_02aug2009.wav

Found here:

https://www.amsat.org/amsat/archive/amsat-bb/200901/msg04335.html
https://groups.google.com/forum/#!topic/fx25/R9gXJUe_NKU

We receive 2 ordinary AX.25 frames and 2 FX.25.

```
$ atest -P+ ande2_demo_02aug2009.wav

Demodulator profile set to "+"
44100 samples per second.  16 bits per sample.  2 audio channels.
8382704 audio bytes in file.  Duration = 47.5 seconds.
Fix Bits level = 0
Channel 0: 1200 baud, AFSK 1200 & 2200 Hz, E+, 44100 sample rate.
Channel 1: 1200 baud, AFSK 1200 & 2200 Hz, E+, 44100 sample rate.

DECODED[1] 0:02.5505 POLLUX-1 audio level = 27(9/9)     _||||____
[0.2] POLLUX-1>CQ,TELEM:MEMS 246642 15.446 15.778 13.990 -0.880 0.113 3.337 -
5.94 13.39 4.39 20.07 20.80 20.42 2.60 13 7 45 <0x0a><0x0a>

DECODED[2] 0:16.1254 KD4HBO-1 audio level = 74(10/10)     _6444____
[0.2] KD4HBO-1>CQ,TELEM:SYS 241800 65535 0 30 0 ffc6 0ee0 ffcb 0bb0 ffed 1268
fe46 0f98 ffe3 10e0 fffb 1168 13.8 5.0 10.4  .13 0.40 1.83 11.06 8.19 8.19 38
51 34 <0x20>

DECODED[3] 0:29.2061 POLLUX-1 audio level = 28(9/8)     _||||____
[0.2] POLLUX-1>CQ,TELEM:SYST 246675 0 0 33 0 002a 1590 0007 1408 002e 1430
0187 11c0 ffff 1068 ffff ffff 0156 08d2 0fbc 003a<0x20>

DECODED[4] 0:46.1236 KD4HBO-1 audio level = 75(10/11)     __77_____
[0.2] KD4HBO-1>CQ,TELEM:SYS 241830 65535 0 30 0 ffb8 0f18 ffd0 0bd0 fff1 1298
fe75 0fc0 ffea 10d8 fff0 1190 13.8 5.0 9.9  .13 0.13 1.79 11.06 8.19 8.19 41
45 42 <0x20>


4 from ande2_demo_02aug2009.wav
4 packets decoded in 6.474 seconds.  7.3 x realtime
```

ande2_test.wav

Found here:

https://groups.google.com/forum/#!topic/fx25/Jy5w6dWYif8

Here we find 4 ordinary AX.25 frames and 3 FX.25.

$ atest -P+ ande2_test.wav

```
Demodulator profile set to "+"
11025 samples per second.  8 bits per sample.  1 audio channels.
348897 audio bytes in file.  Duration = 31.6 seconds.
Fix Bits level = 0
Channel 0: 1200 baud, AFSK 1200 & 2200 Hz, E+, 11025 sample rate.

DECODED[1] 0:02.4812 POLLUX-1 audio level = 89(24/24)     _||||____
[0.2] POLLUX-1>CQ,TELEM:MEMS 322806 2.58 2.57 2.45 17.334 16.887 14.884 -
0.991 0.223 3.07 -6.72 12.27 0.94 21.11 21.89 21.27 2.60 32 22 27
<0x0a><0x0a>

DECODED[2] 0:06.9648 POLLUX-1 audio level = 93(25/24)     _|||||___
[0.3] POLLUX-1>CQ,TELEM:SYST 322839 0 0 33 0 0024 1438 0174 1318 0013 1318
005e 0ea0 001d 0d90 ffff ffff 0156 08d8 0fbe 003a<0x20>

DECODED[3] 0:16.1253 KD4HBO-1 audio level = 115(22/29)     _4444____
[0.2] KD4HBO-1>CQ,TELEM:SYS 318060 65535 0 30 0 fff3 0ac8 ffca 08b8 fe8e 1210
ffe7 0d88 ffb7 1078 ff97 0f38 13.7 5.0 9.9  .17 0.58 1.32 11.06 8.76 8.76 49
44 17 <0x20>

DECODED[4] 0:19.6735 POLLUX-1 audio level = 73(21/18)     _||||____
[0.2] POLLUX-1>CQ,TELEM:MEMS 322938 2.58 2.57 2.44 17.03 17.03 14.884 -0.882
0.227 -2.553 -8.79 -24.64 -8.45 21.11 21.78 21.32 2.60 1 24 31 <0x0a><0x0a>

DECODED[5] 0:24.5102 KD4HBO-1 audio level = 112(36/23)     _6444____
[0.2] KD4HBO-1>CQ,TELEM:SYS 318090 65535 0 30 0 fff3 0b10 ffc7 08d0 fea7 1270
ffe5 0dc8 ffb9 1078 ffa4 0f40 13.8 5.0 9.9  .03 0.31 1.66 11.06 8.76 8.19 46
48 16 <0x20>

DECODED[6] 0:27.5425 POLLUX-1 audio level = 83(24/21)     _||||____
[0.2] POLLUX-1>CQ,TELEM:SYST 322971 0 0 33 0 0184 1520 0000 13d8 001d 13f8
0037 0fd0 0002 0e88 ffff ffff 0158 08d6 0fbe 003c<0x20>

DECODED[7] 0:31.2685 KD4HBO-1 audio level = 109(28/18)     _3446____
[0.1] KD4HBO-1>CQ,TELEM:SYS 318120 65535 0 30 0 fff4 0b48 ffcc 0908 feb8 12b8
ffe6 0dd8 ffb6 1090 ffb4 0f58 13.7 5.0 10.4  .00 0.63 1.74 11.06 8.76 8.19 45
50 14 <0x20>


7 from ande2_test.wav
7 packets decoded in 0.432 seconds.  73.2 x realtime
```

castor0221-2011auto.wav

Found here:

> https://groups.google.com/forum/#!searchin/fx25/%22castor0221-2011auto.wav%22%7Csort:date/fx25/UV5ukmB-riw/pOHqU1RGsnYJ

We receive 4 FX.25 frames.

```
$ atest -P+ castor0221-2011auto.wav

Demodulator profile set to "+"
22050 samples per second.  8 bits per sample.  1 audio channels.
1180262 audio bytes in file.  Duration = 53.5 seconds.
Fix Bits level = 0
Channel 0: 1200 baud, AFSK 1200 & 2200 Hz, E+, 22050 sample rate.

DECODED[1] 0:08.8194 KD4HBO-1 audio level = 199(118/110)     _44447___
[0.3] KD4HBO-1>CQ,TELEM:SYS 62730 65535 0 30 0 fffe 0b60 fff7 0b90 fffe 0c30
ffff 0af0 fe68 0b40 ffdd 0a68 13.6 5.0 11.4  .36 0.64 1.02 20.26 17.96 17.39
16 26 57 <0x20>

DECODED[2] 0:19.6878 KD4HBO-1 audio level = 199(114/108)     854448___
[0.2] KD4HBO-1>CQ,TELEM:SYS 62760 65535 0 30 0 fffe 0b18 fff8 0ba8 fffe 0bf8
ffff 0ae8 fe56 0b88 ffe4 0aa8 13.6 5.0 11.4  .31 1.05 0.80 20.26 17.39 16.81
19 24 57 <0x20>

DECODED[3] 0:32.3424 KD4HBO-1 audio level = 199(117/111)     _4444____
[0.2] KD4HBO-1>CQ,TELEM:SYS 62790 65535 0 30 0 fffe 0af0 fff9 0bb0 ffff 0bd8
ffff 0ac0 fe48 0bf8 ffe9 0ae0 13.6 5.0 11.9  .36 0.73 1.06 20.26 17.39 16.81
21 23 56 <0x20>

DECODED[4] 0:45.3409 KD4HBO-1 audio level = 199(108/102)     _546_____
[0.2] KD4HBO-1>CQ,TELEM:SYS 62820 65535 0 30 0 fffe 0ac0 fffc 0bb0 ffff 0b80
ffff 0aa8 fe3d 0c90 ffeb 0b40 13.6 5.0 11.4  .31 0.86 0.76 20.26 17.39 17.39
23 22 54 <0x20>


4 from castor0221-2011auto.wav
4 packets decoded in 2.107 seconds.  25.4 x realtime
```

castor-1.wav

Found here:

https://groups.google.com/forum/#!searchin/fx25/%22castor0221-2011auto.wav%22%7Csort:date/fx25/UV5ukmB-riw/pOHqU1RGsnYJ

We receive 3 FX.25 frames.

$ atest -P+ castor-1.wav

```
Demodulator profile set to "+"
44100 samples per second.  16 bits per sample.  2 audio channels.
6422816 audio bytes in file.  Duration = 36.4 seconds.
Fix Bits level = 0
Channel 0: 1200 baud, AFSK 1200 & 2200 Hz, E+, 44100 sample rate.
Channel 1: 1200 baud, AFSK 1200 & 2200 Hz, E+, 44100 sample rate.

DECODED[1] 0:07.9973 KD4HBO-1 audio level = 198(93/43)     ___844444
[0.5] KD4HBO-1>CQ,TELEM:SYS 214950 65535 0 30 0 fffe 0560 fffe 0530 fffe 06d0
fe99 11c8 fffe 0fd8 ffde 1068 13.6 5.0 10.4  .03 0.64 0.89 17.39 14.51 14.51
7 34 13 <0x20>

DECODED[2] 0:17.6036 KD4HBO-1 audio level = 198(92/54)     ___444666
[0.5] KD4HBO-1>CQ,TELEM:SYS 214980 65535 0 30 0 fffe 0548 fffe 0508 fffe 06d8
fe96 1248 fffe 0fc0 ffe0 10c8 13.6 5.0 10.9  .27 0.68 0.85 17.39 14.51 13.94
5 35 17 <0x20>

DECODED[3] 0:25.1442 KD4HBO-1 audio level = 199(97/36)     ____77788
[0.6] KD4HBO-1>CQ,TELEM:SYS 215010 65535 0 30 0 fffe 0538 fffe 04d0 fffe 06c0
fe94 12e0 fffe 0f98 ffd6 1120 13.6 5.0 10.9  .45 0.77 0.76 17.39 14.51 14.51
4 35 21 <0x20>


3 from castor-1.wav
3 packets decoded in 4.931 seconds.  7.4 x realtime
```