Short Training Sequence for the IEEE OFDM Standard

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The current draft text of the IEEE OFDM standard specifies the following short training sequence:

S=2*{0, 0, 1+j, 0, 0, 0, –1+j, 0, 0, 0, 1+j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, 1+j, 0, 0, 0, –1-j, 0, 0, 0, 1-j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, 1+j, 0, 0}

One of the main reasons to select this particular sequence was the possibility to use a simple matched filter with binary coefficients to perform a correlation of the input training signal with the expected reference signal. Figure 1 shows the correlation functions for fractional delay offsets of zero and half a sample, respectively. The correlation sidelobes more than two samples away from the main peak are 13.3 dB below the peak amplitude. A low sidelobe level is important, because OFDM symbol timing is derived from the time of the correlation peak. Especially in multipath channels, correlation sidelobes tend to increase the timing error, thereby increasing the packet error probability.

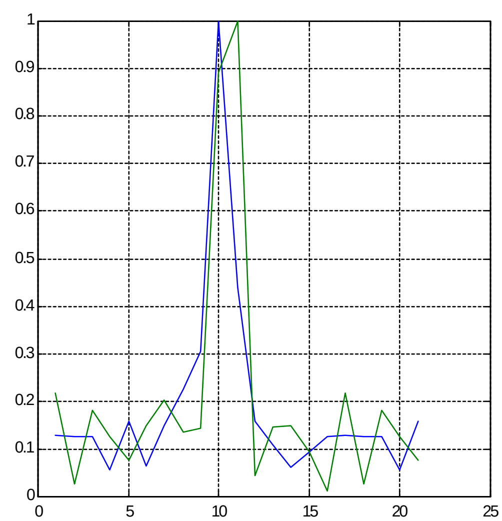

Figure 1: Correlation output of training signal correlated with {-1-j, 1-j, 1, j, j, 1, 1-j, -1-j, 1-j, 1, -j, 1-j, 1,-1- j, 0, 1+j}

As pointed out by Breezecom at the September IEEE meeting, the fact that the short training symbols have alternating signs make them vulnerable to a DC bias. To remedy this problem, it was proposed to move the short sequence values 2 subcarriers away from DC, so *S* becomes:

S=2*{1+j, 0, 0, 0, –1+j, 0, 0, 0, 1+j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, –1-j, 0, 0, 0, 1-j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, –1-j, 0, 0, 0, 1+j}

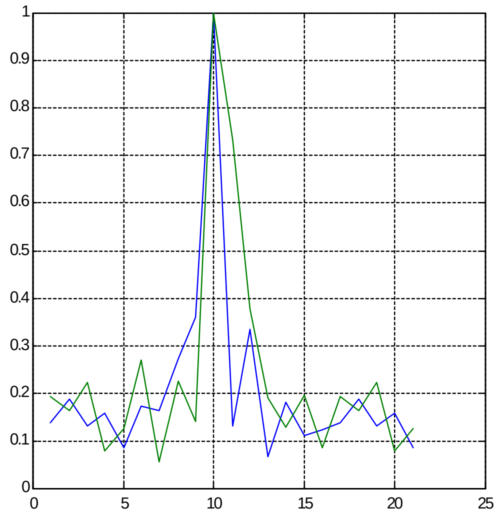

Figure 2: Correlation output of modified training signal correlated with {-1-j, 1-j, 1+j, j, 1-j,1-j, -1-j, -j, 1+j, -1-j, -1+j, -1+j, -1+j, 1+j, 1, -1-j}

As figure 2 shows, the penalty of the modified training signal is the increased correlation sidelobe level when using a simple matched filter; the sidelobes more than 2 samples away from the main peak are now down by 11.4 dB.

To find out if better codes exist, a search was performed among a set of 16 complementary sequences of length 12. The reason to search complementary sequences is the fact that they give a low PAP ratio of 3 dB, which reduces the quantization errors when approximated by a binary (or ternary) sequence. The same method as suggested by Breezecom was used to put the subcarriers only on multiples of 4, in order to get repeating non-inverting short training symbols.

The best code found was:

S=2*{1+j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, –1-j, 0, 0, 0, 1-j, 0, 0, 0, -1-j, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, –1-j, 0, 0, 0, 1+j, 0, 0, 0, –1+j, 0, 0, 0, 1+j}

Figure 3 shows the correlation properties for this code, with sidelobes that are 13.9 dB below the main correlation peak. An additional advantage is that the matched filter taps are simpler than in the previous case; there are only 14 non-zero taps, of which 9 are purely real or imaginary, so they can be implemented by a simple I/Q swap and an inverter.

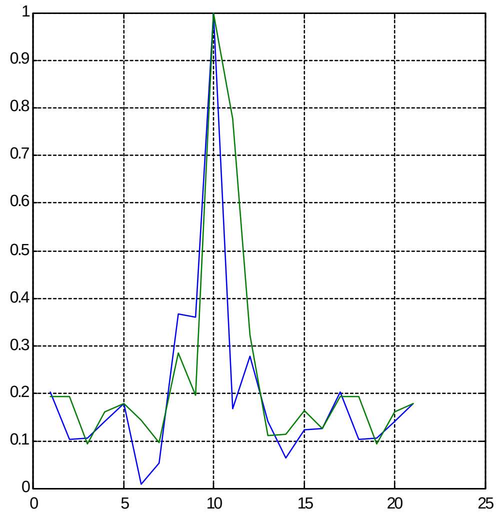

Figure 3: Correlation output of modified training signal correlated with {0, -1, j, j, -1,-1+j, j, 1-j, 1, j, -j, -j, 0, 1+j, 1-j, 1-j}

A search was also made for training symbols which do not use subcarrier numbers that are a multiple of 4. In this case, the best code was:

S=2*{0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1+j, 0, 0, 0, 1+j, 0, 0, 0, -1+j, 0, 0, 0, -1+j, 0, 0, 0, 1-j, 0, 0, 0, 1-j, 0, 0, 0, 1+j, 0, 0, 0, 1-j, 0, 0}

Figure 4 shows the correlation properties of this code together when used together with a simple matched filter. The sidelobes are 15.2 dB below the correlation peak. This is the best code found with respect to the correlation sidelobes, but because of the disadvantage of increased vulnerability to DC bias, it is recommended to use the code from figure 3.

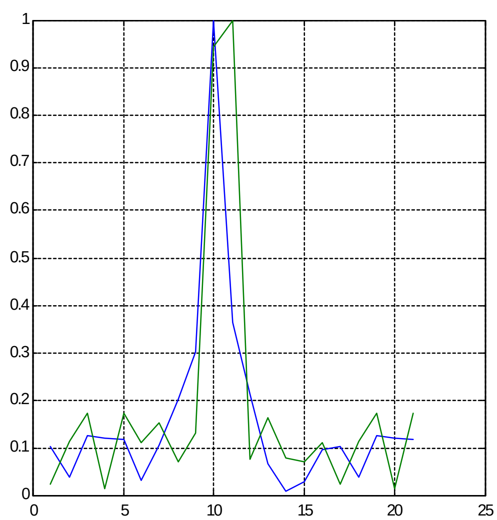

Figure 4: Correlation output of training signal with inverting short training symbols, correlated with {-1, 0, 1+j, 1, 1-j, j, 1+j, 1, 1, -1-j, -j, 1, 1, j, j, 1-j}

Conclusions

A search was made to find good codes with low correlation sidelobes when used together with a simple matched filter with binary I/Q tap values. The best code found has sidelobes that are 15 dB below the correlation peak, but it has the disadvantage of producing alternating sequences, making it more vulnerable to DC bias. Therefore, it is recommended to use the following code, which produces 4 non-inverting sequences when passed through a 64-point IFFT. The correlation sidelobes of this code are almost 14 dB below the main correlation peak when a simple matched filter is used.

$$S=2*\{1+j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1-j, 0, 0, 0, -1-j, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1+j, 0, 0, 0, 1+j\}$$