# Addendum – Quantized Time-Scale Hologram

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During development and testing of the LB28 I3 modes that utilize pulse train standing waves, specifically the testing of fixed absolute phase recovery with extrapolation, it has become apparent that not only are these effective techniques for phase recovery, but that the signal produced by the interposed three phase signal generator is in fact a quantized time-scale hologram with some very useful properties. These include:

- increased resilience to phase noise
- characters in the message having the appearance of being locked together or entangled thus eliminating phase drift
- ability to take multiple samples from the hologram to further enhance noise resilience by averaging out the noise.

This document aims to explore these capabilities of the I3 modes and the related noise reduction techniques.

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# Quantized Time-Scale Holographic Photons / Phonons

Utilizing pulse train standing waves for phase extraction requires a signal generated by the interposed three phase signal generator or similar as detailed in the earlier published LB28 design document.

The signal generated by this process is analogous to a time-scale hologram and can be thought of in similar terms to that of a photon or phonon...i.e. a packet of light or sound quantized by the number of pulses in the packet; depending on weather the transmission utilizes electromagnetic waves or sound waves, the process is somewhat similar. For electromagnetic waves, the signal creates a quantized time-scale photon hologram and for sound waves it creates a quantized time-scale phonon hologram.

The hologram / observer have two degrees of freedom; time and scale. These translate to the disposition i.e. the start of the decoding process relative to the signal start representing time and the number of pulses utilized in the pulse train for a specific decode representing scale.

The hologram can be processed from multiple perspectives. The number of permutations / perspectives is derived from the triangular number for the given mode. For example a mode with 64 pulses per block, i.e. 32 pulses per 3 bit sequence has $T_{32}$ or 528 permutations. In reality, this number is $T_{32}$ -3 as the pulse train length is truncated to a useable length of pulse train length divisible exactly by 3.

Any of these 525 permutations can be used to make a successful decode. The more noise resilient decodes are from signals that contain the highest number of pulses.

## Extrapolation

Extrapolation to acquire a single sample with the maximum number of extraction points has proven not only that the three phase signal functions as a time-scale hologram, but has also proven to be a highly effective method to further reduce noise and increase signal decode accuracy. However, regardless of the signal to noise ratio, extrapolation of a single sample, although highly effective, is not yet sufficient to achieve a 0.0 BER over a tested 348 bit sample; in combination, all of the techniques described are able to bring the decode to a level near 4 $e^{-3}$. Interestingly at high SNR the 1 or 2 bit errors always occurred at exactly the same place in the test with the same character sequence for example ck often resolved to dk. This is a future area for further research to determine how character sequencing impacts the decode and to test if techniques such as differential encoding and gray codes are the answer for this method of phase extraction.

Additional techniques such as forward error correction have been successfully incorporated to increase decode accuracy even further.

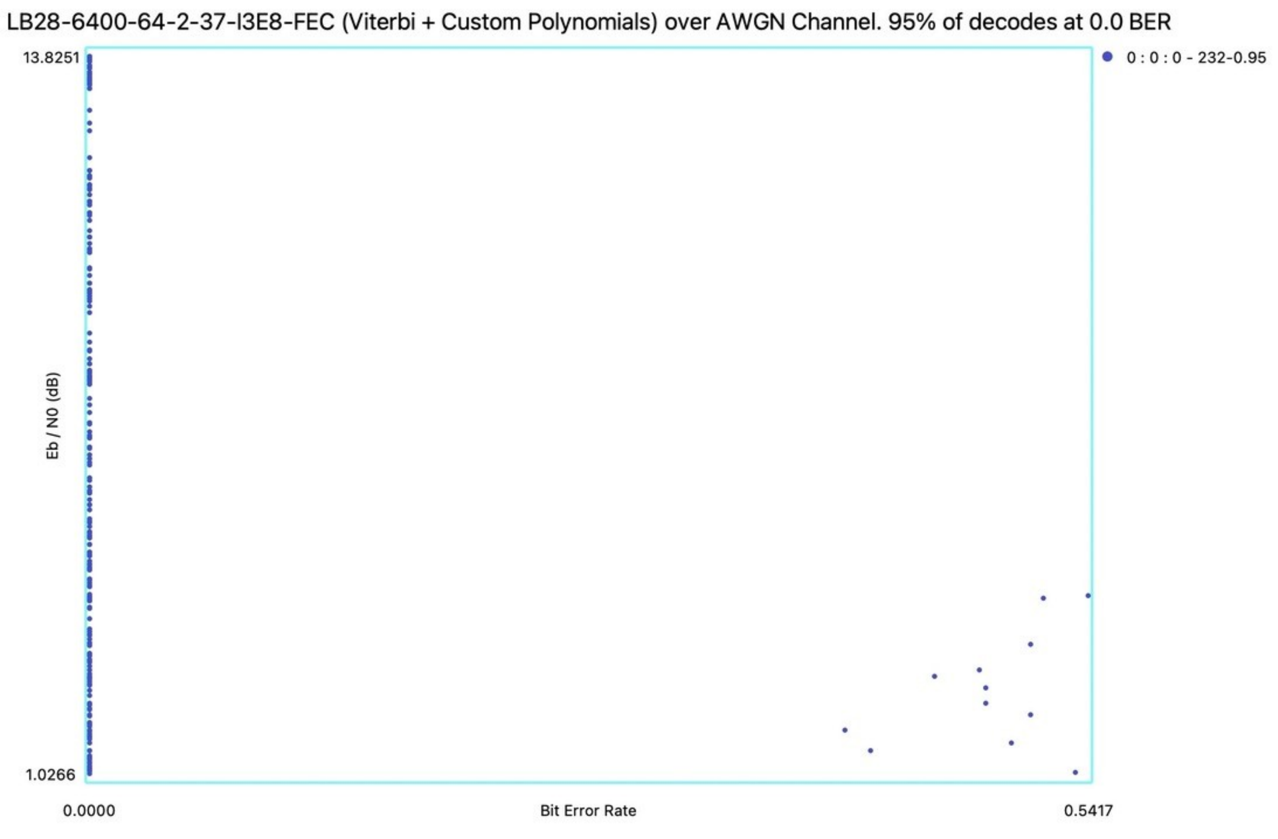
# Forward Error Correction

## Viterbi + Custom Polynomials

The following diagram shows the combined effect of multiple techniques including interpolation, extrapolation, fixed absolute phase rotation based on rotation tables, pulse train standing waves and Viterbi error correction. The mode in the diagram has a carefully designed signal generator phase pattern along with carefully selected root raised cosine alpha and T coefficients as well as a number of other carefully designed processes.

The Viterbi decoder process utilizes a ½ convolutional code encoder with custom generator polynomials and no puncture code i.e. 1 bit in and 2 bits out.

The combination of all of the above techniques is a 95% success rate at Eb/N0 above 1.0 to bring the error rate to 0.0 BER for a perfect decode. In the test, 1.0 Eb/N0 is equivalent to a -26.67 SNR level.



## Extrapolation with Multiple Hologram Samples

These techniques can be extended to take several samples of the quantized time-scale hologram and then aggregate the bit sequences into a single bit sequence and send this to the Viterbi decoder for final processing. This is currently a work in progress for the prototype to determine the extent to which this impacts the decode quality.

# Maximum Bit Rate

Other than higher capacity constellation encoding such as 16 QAM, 32 QAM etc, there are a number of techniques that the holographic I3 modes can utilize to increase bit rate. These include:

- Reducing the number of pulses per block
- Reducing the block size
- Frequency Multiplexing
- Reducing the number of pulses required to encode bits
- More efficient FEC algorithm

Through experimentation, all of these these techniques have proven to be effective with some limitations. Currently the highest bitrate achievable, using a non-frequency multiplexed LB28 I3 mode with a 37Hz carrier spacing, is 64.44 bits per second. This mode utilizes 8 pulses per block, a 400 sample block size, 8kHz sample rate, 37 Hz carrier frequency separation with ½ convolutional code FEC and can achieve a 0.0 BER at around 6 Eb/N0 dB (-11.7 SNR).

## Holographic Frequency Multiplexing

With frequency multiplexing, bit rate can be multiplied many times over; preliminary testing using the latest prototype indicates that the quantized time-scale hologram can be paired with another similar hologram at a different frequency to double the bit rate while also achieving a 0.0 BER with no Inter-Symbol Interference.

For example, a single hologram can be combined with a second hologram with equal characteristics using a frequency separation of around 76 Hz. As a point of note, solving for hologram frequency separation and downconvert shift simultaneously provides an effective technique to derive the precise values required for holographic frequency multiplexing. This combined hologram is also able to achieve a 0.0 BER. Constraints such as orthogonal carriers or signal spacing buffer zones are unnecessary.

This combined hologram can then be paired again with a similar combined hologram but using a different separation frequency of around 160 Hz. This can also achieve a 0.0 BER. This pair of pairs combination increases bit rate fourfold.

Using this holographic frequency multiplexing pairing technique, the bit rate has been increased from 64.44 bit per second to 257.76 bits per second using approximately 320 Hz of spectrum. Extending this out, a similar mode can theoretically achieve a 1933 bit rate over a 2400Hz spectrum by using holographic frequency multiplexing.

Bit rate can be further increased by reducing the number of pulses used to encode a character from 8 to 4 or 2 i.e. a twofold and fourfold increase respectively, however this will require a switch from I3 type modulation to I2 or I1. As a point of note, the number of phases used to generate the standing waves is a separate and distinct concept from the way in which pulses are combined. The I3 modes currently use 3 phases and 3 pulse groupings for combining. An I1 mode would use multiple phases but essentially eliminate the combining step thus relying on adjacent pulse addition only in the downconvert stage. An I2 mode can utilize multiple phases along with 2 pulse combinations. These are currently areas for further research to determine effectiveness.

Additionally, using a more efficient FEC encoding or removing FEC entirely could potentially double this rate again. Combining these different techniques has the potential to match and even exceed both the bit rate and noise resilience characteristics of the high performance Orthogonal Frequency Division Multiplexing (OFDM) modes. Although currently theoretical, the building blocks for this have already been successfully proven.

# Observer

The pulse train standing waves / amplified phase waves occur at points along the pulse train. Technically speaking, these could be considered as a special class of standing wave know as rotating standing waves, however this classification is somewhat ambiguous as it depends entirely on your frame of reference i.e. what is rotating and relative to what? Is it the location of the standing wave that is fixed with the wave phase rotating or is it the other way around with the wave phase being fixed and the location of the standing wave rotating? This will be explained in more detail in the next section.

There are multiple different ways that these amplified phase waves can be interpreted depending on the perspective of the observer. These include:-

1) As a sequence of amplified phase wave pulses received by a stationary observer.
   a) When the frequency of the observation interval is synchronized / precisely aligned with the carrier wave frequency of the amplified phase wave and the RRC pulse peaks are also synchronized with this carrier frequency, the result is a precisely formed standing wave.
   b) If the frequency of the observation interval at the stationary observer is not synchronized with the carrier wave frequency, the observer will see a sequence of phases which when combined give a resulting phase that is offset by an amount depending on the disposition.
2) If riding along with the waves as they propagate, the effect will be one of a true standing wave on the pulse train.

So to be precise, it really depends from which context the observer is observing the resulting waves.

# Absolute Phase

Think for a moment about traveling along with the wave at the speed of light as in point 2 of the previous section. Think also of this in the context of the phase wave simulation as provided in the LB28 main document. The simulation diagram shows the amplified phase wave at a single point in time.

Now imagine a window at the peak of the RRC pulse through which the phase of the amplified phase wave is observed. While it is true that the phase of the amplified phase wave changes as it propagates, it is also true that the window through which this is observed as we travel along with the waves has also changed. Both the amplified phase wave and the RRC pulse peak have propagated or evolved in time at the same rate and in the same direction. The net result is that the amplified phase wave as measured in relation to this observation window has remained constant or fixed thus giving the basis for an absolute phase extraction. A key point is that the phase of the amplified phase wave is measured in relation to the RRC pulse.

Now remember from the earlier explanation that the measured phase is a result of both phase and magnitude. The phases at the pulse peaks and standing wave nodes are the phases that will determine the resulting phase. In this context, effective standing wave phase patterns can be those where the amplified phase wave is concurrent with or near to the RRC pulse peak as this maximizes the amplified phase wave / standing wave signal while at the same time reducing any non-standing-wave signals from being amplified by the RRC pulse peaks. A key point here is the location of the window through which the phase is measured relative to the RRC pulse. In the prototype application, downconvert_shift is used to adjust this window location. The precise value will vary depending on a number of parameters including the phase pattern chosen as well as the nature of any holographic frequency multiplexing. This value is absolutely critical for a successful decode.

While the above description is incomplete in the sense that it does not cover the full set of mechanisms of the hologram such as the pulse addition and pulse combination techniques used, it is my best attempt so far at explaining the central component that facilitates extraction based on absolute phase. Proof that this method of extraction actually works can be found in the OSMOD prototype application v0.1.0 that uses holographic (I3) modulation. Specifically the I3E8 and I3F modes that rely on fixed absolute phase extraction. The I3E8 mode described earlier achieves a 95% success rate for a perfect 0.0 BER decode over a 348 bit sample at SNR levels above 1.0 Eb/No dB (-27 SNR).

## Quantized Observation

Measurement can also be thought of in terms of a quantized observation. When phase is measured at a location relative to the RRC pulse, each RRC pulse will have an absolute phase. As a sequence of RRC pulses are received in sequence, the combination of these pulses each with their own absolute phase, are combined in a similar way to that in which wave phases are added to derive a resulting phase. So at a given observation scale in which a set of pulses are used to derive phase, the resulting phase will be the combination of all of the individual RRC pulse phases at that scale. As described earlier, this resulting phase is relative to the hologram disposition i.e. the number of pulses in the measurement (the scale) as well as the offset from the start of the hologram (time offset). In this sense, measuring the phase of a time-scale hologram and measuring the phase of regular waves is similar albeit that the former represents phase change as discrete steps whereas the latter represents phase change as a continuous flow. In addition, the difference between these two approaches is that the hologram uses an absolute phase reference whereas the regular waves do not.

# Entanglement

Extracting the encoded phase of a quantized time-scale hologram depends on knowing which hologram sub-part of the whole hologram has been retrieved. The sub-part and its specific details, also referred to as the disposition, are a combination of the number of pulses and the offset of the start of the pulses relative to where they should start. Once the disposition is known, then the phase can be extracted from an absolute frame of reference. Several processes facilitate this, including:-

1. Determine the rotation of the detected hologram and reference a pre-calculated lookup table. This rotation plus the detected pulse sequence scale is used in conjunction with the lookup table to obtain absolute phase.
2. Taking a sample at an exact point in time relative to the encoded block and applying a uniform scale disposition to each sample gives the relative phase of each sample. This technique could be utilized with differential encoding. The advantage is that an initial rotation / initialization sequence is not required. The disadvantage is that the extrapolation technique as described cannot be utilized so the scale i.e. the number of pulses used in the decode is dependent entirely on the sensitivity of the receiver and the extent to which the pulse train length is aggregated over time.
3. Using a receiver sensitive enough to receive all pulses thus obtaining a known disposition and an absolute phase decode. If we take a specific example of a single 3 bit encoding representing half of a base 64 encoded character, sent out as a pulse train of 32 pulses, when this is received at the observer, as long as the measuring equipment is sufficiently sensitive to receive all of the 32 transmitted pulses, then this constitutes a fully defined hologram with a known disposition; the first pulse and all subsequent pulses were received thus there is no relative time offset and because all 32 pulses were received, the full disposition is known. The advantage is that in this special case, there is no requirement to apply any rotation or to have an initialization or extrapolation sequence tacked onto the front of the signal; the phase as decoded is an absolute phase decode. The disadvantage is that signal decode accuracy degrades rapidly even at relatively low levels of noise; if one or more pulses are not detected then this causes the accuracy of the decoded phase to degrade.

The concept of absolute phase recovery presents a framework in which all signals encoded using a quantized time-scale hologram can be considered to be entangled. However, entanglement is simply an intrinsic property of absolute phase recovery using time-scale holograms. This framework presents an intuitive basis from which to understand and explain entanglement.

# Discrete Phase Space

A natural consequence arising from quantized time-scale holograms is that the phase space could be considered as a discrete phase space where the phase transitions are not smooth but instead become discreet steps in phase or phase jumps.

To investigate this idea via simulation, the rotation tables have been used as the basis for calculating constellation shift. A resolution of 1 part in 100,000 i.e. increments of 0.001 over a scale from 0 to 100 is used. This is achieved by looking at each value in the rotation table for both frequencies (each value represents rotation between 0 and 2 * pi) and then dividing this value by pi / 4 which represents the 8psk constellation divisions. What is left is a value that shows the degree of constellation shift within each pi/4 slice of the constellation. This shift is then multiplied by 100 and a modulo 100 value derived to give 3 decimal point value of 0 to 100. These values are sorted and a minimum increment value identified. Mode LB28-6400-64-2-37-I3E8-FEC has been used as the basis for these tests. The results for each scale are shown below:-

| Scale | Minimum Increment |
|---|---|
| 3 | 0.003 |
| 4 | 0.084 |
| 5 | 0.093 |
| 6 | 0.106 |
| 7 | 0.065 |
| 8 | 0.065 |
| 9 | 0.022 |
| 10 | 0.022 |
| 11 | 0.014 |
| 12 | 0.069 |
| 13 | 0.042 |
| 14 | 0.042 |
| 15 | 0.12 |
| 16 | 0.12 |
| 17 | 0.125 |
| 18 | 0.066 |
| 19 | 0.066 |
| 20 | 0.066 |
| 21 | 0.12 |
| 22 | 0.12 |
| 23 | 0.183 |
| 24 | 0.417 |
| 25 | 0.317 |
| 26 | 0.317 |
| 27 | 0.952 |
| 28 | 1.644 |
| 29 | 1.342 |
| 30 | 3.291 |
| 31 | 6.964 |
| 32 | 17.59 |

A second observation from the constellation shift tables can be seen in the following example. The table below for scale 18 shows that the phase jump values vary considerably from one value to the next. These values as well as the size of the phase shift jumps are non-linear.

```
Scale 18 :-
minimum increment: 0.066
sorted_unique_jumps: [0.246, 0.312, 3.19, 6.252, 7.065, 8.542, 11.215,
11.846, 20.634, 21.106, 26.44, 30.752, 38.358, 38.983, 40.906, 47.14,
49.903, 54.873, 56.024, 56.54, 73.216, 78.458, 78.555, 81.191, 83.275,
84.179, 84.344, 86.823, 87.939, 95.238]
```

A third observation can be found by comparing the constellation shift table values for scale 24 below with the table for scale 18 above. As can be seen, the constellation shift value of 40.906 in the above table is not the same as the 40.813 value in the table below. All values are calculated to three decimal places. What this translates to is that the precise rotations required, although appearing similar on the surface, have small observable differences that allow a determination to be made about disposition of the decoded signal i.e. was the decode at scale 18 or was the decode at scale 24 and what the relative time offset is.

```
Info: Scale 24 :-
Info: minimum increment: 0.417
Info: sorted_unique_jumps: [0.732, 18.408, 23.587, 26.632, 29.386,
40.364, 40.813, 49.506, 56.025, 58.911, 60.413, 62.296, 62.968, 75.892,
84.245, 84.662, 88.389, 90.114]
```

With respect to discrete phase space, two of the above observations i.e. the minimum increment at each scale and the comparison of rotations across scales are interesting. While these observations may suggest that phase space has characteristics of a system of discrete units, the precise nature of these units is unknown. Any further analysis of this is outside the scope of this document.

The above three effects are all potentially useful as the basis of a constellation shift extrapolation technique as explained in the next section.

# Constellation Shift Extrapolation

Instead of relying on an initialization sequence at the front of a transmission, this technique looks at how the decoded 3  bit sequence's phase position lines up relative to the constellation i.e. the precise offset within a 1/8 constellation slice for 8psk.

Absolute phase is absolute phase and the constellation locations will also be absolute; although the constellation locations will vary with disposition, the calculations performed in the previous section show that these constellation shift values are discrete jumps in phase and have similar unique fingerprints depending on the hologram disposition. This allows extrapolation to be achieved based on constellation shift only.

The values required for this can be aggregated over a number of unknown message characters and an accurate measurement obtained without the need for an initial extrapolation or rotation sequence. The precise character encoding is irrelevant. The only information required is the offset within the 8psk constellation slice for each of the characters. This is then compared with a constellation shift lookup table using a known pulse-length / scale to identify which dispositions match in a similar way to the previous technique. Due to the smaller tolerances involved compared to the previous extrapolation technique, it is likely that multiple re-samples of the hologram will be required to determine disposition and perform extrapolation.

It is unknown at the present time how effective this technique will be for different levels of AWGN and is planned for future research. This technique becomes possible only when combined with holographic modulation and absolute phase extraction.