Concurrent codes: A holographic-type encoding robust against noise and loss.

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Abstract.
Concurrent coding is an encoding scheme with ‘holographic’ type properties that are shown here to be robust against a significant amount of noise and signal loss. A simple and practical scheme has been tested that displays perfect decoding when the signal to noise ratio is of order -15dB. The same scheme also displays perfect reconstruction when a contiguous block of 40% of the transmission is missing. In addition this scheme is 50% more efficient in terms of transmitted power requirements than equivalent cyclic codes. A simple model is presented that describes the process of decoding and can determine the computational load that would be expected, as well as describing the critical levels of noise and missing data at which false messages begin to be generated.

Introduction
Concurrent coding is a little known technique developed by Baird, Bahn and Collins (BBC)[1][2][3][4][5] that was devised to offer a means of information encoding that could be resistant to the effects of jamming (intentional or accidental) without the need for the communicating parties to encrypt their communications with a shared key. The technique makes use of properties of an asymmetric binary channel where indelible marks representing 1’s are placed into a communication channel with the absence of a mark representing a zero. The mark is typically given by the presence of energy in a time or frequency channel. Binary coded symbols, referred to herein as messages, are dissected, encoded and distributed throughout a much larger transmission. The name concurrent code arises from the ability to superimpose codes through a logical OR process. Many such concurrently coded messages can be overlaid into the transmission with the result being that each message is ‘holographically’ encoded into the transmitted codeword. This is to say that, broadly speaking, each part of the transmission codeword contains relationships with every message that is encoded within it. In the field of optical science it is appreciated that each fragment of a hologram can reproduce a version of the entire hologram from which it came (albeit at reduced quality). It is therefore reasonable to speculate that a holographic encoding technique might exhibit similar qualities, such that missing parts of a transmission could be reconstructed.

Resistance to jamming is arises by requiring a jammer to expend large amounts of energy across frequency and/or time bins in an effort to block communications. The emphasis in this paper is more general than the case of jamming, as we shall see concurrent codes offers the potential for significant resistance to the effects of noise and can provide robustness against loss of information in a number of ways.

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Building robustness into data transmission is necessary and well established with methods of parity checking, forward error correction, interleaving, Viterbi coding\[6\] or turbo coding\[7\] all allowing data corruption to be identified and/or corrected. These techniques generally operate on binary symmetric channels where parity information is encoded into a data stream and connects bits locally with their neighbours, allowing errors in individual bits to be corrected. Concurrent coding differs because it encodes whole messages (or symbols) and distributes their integrity information globally throughout the transmission rather than locally. This is of course similar to the use of interleaving - distributing neighbouring bits into an array type structure to combat the effects of burst errors - but as we shall see is more flexible and resilient.

The requirement for indelible marks limits the modulation schemes able to carry concurrent coding to binary formats – zeros can be converted to ones, ones cannot be deleted – therefore symbolic formats cannot be used as one symbol can be transmuted into a different one. Schemes such as on-off keying are particularly well suited but others such as ASK and FSK are also viable.

**Concurrent codes**

The principle behind concurrent coding is well described in [1][2][3] but briefly described here. Concurrent coding uses the unique linear sequence of 0’s and 1’s in a message word to generate a pattern of 0’s and 1’s uniquely distributed across a larger codeword space. A message is broken down into linearly expanding sub-sequences of bits, each of which is then passed through a hashing function. The output of the hashing function is used as the address of a mark to be placed in the codeword space. For example the message 1101 will produce addresses from the hash sequences H(1), H(01), H(101) and H(1101). Multiple messages can be combined into a single codeword before transmission, as shown schematically in Figure 1.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** A schematic diagram of producing codewords from messages. The upper portion shows the production of a codeword from a single message, the lower portion shows the result of adding hashed messages into a common codeword space.

The decoding of the message proceeds by trying the values 0 and 1, (the first potential message bits) and passing them through the hashing function, then examining the received codeword. If a mark is found at the position indicated by the output of the hash functions then the message value is retained for further analysis. If no mark is found all possibilities with the input sequence cannot be found and analysis not pursued. For the retained values the next step in the sequence is examined with both 0 and 1 appended i.e. if H(1) found, next step is H(01) and H(11), retaining those attempts that result in an associated mark present in the codeword. The process is repeated for the relevant number of bits in each message. The process forms a decoding tree as represented in Figure 2.
Figure 2. A representation of the decoding tree. Grey boxes represent dead branches where no corresponding mark was found in the codeword.

The effect of noise or jamming that adds marks into the codeword is also shown by the highlighted bit in the codeword. It can be seen that whilst initially extra branches are retained they are quickly lost as no marks corresponding to messages are found.

With a large number of messages present or significant noise there will be routes through the decoding tree that result in messages not actually present in the original codeword. These false messages are referred to as hallucinations. To help reduce hallucinations a number of constant value, (0) checksum bits are appended to each message (e.g. 1101 becomes 001101).

**The Hash Function**

Of particular significance to this technique is the hash function that is used. As this function can be called many times, particularly in the decoding tree the processing requirements can be a limiting factor in the performance and could therefore limit bandwidth and usability. Indeed BBC recognised the impact of the hash function and developed the Inchworm Hash to speed up the process [4] and subsequently the Glowworm Hash [8]. Simplicity and speed of implementation are important factors in translating concepts into viable technologies. The driving principle of the hash function is redistribution around the codeword, not in this first instance of providing security in the encoding. For this purpose a PRBS generator was found to be a suitable and simple variant of the hashing function with the added attraction of simplicity of implementation.

A 10 bit PRBS addresses a codeword space of 1024 bits and enables 8 bit messages with 2 checksum bits to be used. A PRBS is attractive because it can be implemented in either hardware or software without requiring a large number of operations. The PRBS used in this work is represented in Figure 3.

Whilst this approach does not hash sub-sequences as presented earlier, each progression through each bit of the message produces an output state dependent upon the current bit and all the previous bits. The output of each cycle is used as the address for placing a mark in the codeword.

Figure 3. A representation of the 10 bit PRBS used for hashing.
Implementation

A concurrent code model was coded using LabView software with a view to exploring the performance of this technique with a variety of data conditions and identifying strengths and weaknesses. A word about the scale. In this work simplicity and practicality are driving principles behind the design. For this reason the codeword length was kept relatively short at 10 bits, allowing 8 bit messages to be encoded (convenient for transmitting ASCII codes for example) and equally allowing a simple PRBS to be used. The BBC implementations often focussed on much longer codewords with individual messages as long as 200 bits as well as more involved hashing algorithms. One downside of this is significant latency in the final decoding of the transmission; an issue that is sometimes encountered with interleaving where the effect is much reduced in comparison to concurrent coding. For concurrent coding the entire codeword must be received before the message decoding process can begin, followed by what could be a lengthy computationally involved decoding process. The opposite approach is chosen here, to keep the latency down with short codewords and to reduce computational load with simple hashes.

A chosen number of randomly generated 8 bit messages were passed through a concurrent coding algorithm and a codeword prepared from the overlaying of all the encoded messages. This prepared codeword was then degraded through the addition of a controllable level of noise marks into the codeword. An important characteristic of Concurrent Coding is that genuine messages placed into the codeword cannot be deleted, they can only be obscured by the presence of hallucinations, a feature arising from the indelible marks used and the binary asymmetry. Thus the level of hallucinations generated is a critical parameter in assessing the signal to noise level.

To provide a comparison with conventional techniques an ‘equivalent’ encoding system was also implemented. Providing ‘equivalence’ requires taking the same size of messages and encoding to correct for transmission errors with a codeword of the same length. In this case 8 bit message were halved and encoded with an H(8,4) Hamming code. The results were then interleaved into a 1024 bit codeword space. The prepared codeword was then subjected to noise and degradation before being decoded.

When adding noise to into the codeword a standardisation was used where the number of marks present for a single message was defined as 0dB. **Figure 4** plots the number of hallucinations produced as the noise level is increased, with a fixed number of 10 messages encoded. Hallucinations start to appear at a noise level around 15dB. The generation of hallucinations was found to be dependent upon the initial state of the PRBS register and hence values that generated no additional hallucinations at lower noise levels were used.
Figure 4. The number of hallucinations vs the level of noise introduced to the codeword.

Figure 5. The effect of noise upon the Interleaved Hamming encoding. The error fraction is the number of genuine messages that are incorrectly decoded relative to the original messages.

The effect of the number of messages encoded was investigated and found that, even with some noise introduced, no hallucinations were created with 80 messages encoded, although the decoding time increased significantly. In comparison the Hamming interleaved code behaved as shown in Figure 5 to the addition of noise.

Missing Data

At this point it is helpful to introduce some concepts before tackling the effects of missing data chunks in the codeword. For an N-bit codeword there are \(2^N\) possible unique combinations. As unique messages are added to the codeword the number of combinations available is reduced as \(2^N - m\), where \(m\) is the number of messages. The number of common marks is dependent upon the matching specific sub-sequences (starting from bit index zero) between different messages. For a population of \(m\) messages there will be a minimum number of sub-sequence matches within the population, given by \(\text{floor}(\log_2(m))\), where floor represents the largest integer value less than the argument. Writing the number of messages as:

\[ m = 2^a, \]

\(a\) is the effective number of bits in common between messages and therefore represents the number of post-hash marks shared by those messages.
\[ a = \log_2 m \]  

The number of marks produced for \( m \) messages is then 

\[ Z(m) = Nm - m \log_2 m \]  

The average number of marks produced for a given number of randomly generated messages was recorded. This data is shown in Figure 6 with up to 100 included messages. The estimated number of marks is also shown. This estimate displays the trend of the number of marks but consistently underestimates the number of marks produced by more than the standard deviation of the measurements – typically 2 standard deviations for \( m > 10 \). This discrepancy is most likely due to properties of the PRBS hash function and requires further investigation but does adequately describe the trend of mark generation.

![Figure 6. Measured and estimated number of codeword marks for a given number of included messages.](image)

Given the number of messages, the number of marks can be determined and hence the signal level. Clearly introducing more messages improves the signal to noise, but does so at the expense of speed of decoding. It is also worth indicating that when the codeword contains a large fraction of message marks, the relative effect of any noise is enhanced because a single mark can be associated to many potential message marks. This will add significantly to the processing overhead of the decoding and increase the number of hallucinations. Maximising the number of messages present in the codeword may not be the optimum strategy for guarding against the effect of noise or jamming. There should be an optimum message fraction to reduce jamming effectiveness and ensure robustness.

Knowing how many marks are produced from a given number of messages it is natural to consider the situation where a codeword is received without knowledge of how many messages it contains. The receiver would then wish to determine, given a number of marks received, how many messages should be expected. Solving equation (2 for the number of messages \( m \) results in:

\[ m = \frac{-Z \log_2 W \left( -2^m Z \log_2 \right)}{W(-2^m Z \log_2)} \]  

Where \( W \) is the Lambert W function which has to be evaluated explicitly through a series expansion of the form
\[ W(x) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}n^{n-2}}{(n-1)!} x^n \]  

which is only reliable for real values of \( x < 0.4 \). Calculating the number of messages in a code word given the number of marks was performed and plotted with the calculated number of marks from a known number of messages. Calculating the number of expected messages is really only effective as a check that the decoding process has produced sufficient messages or indeed too many messages.

**Effects of Intermittency**

Intermittency in a signal can arise due to misalignment of directed beams, environmental effects such as scintillation or even fading. Removal of a contiguous chunk of data can be catastrophic for most encoding methods. To test the earlier assertion that missing data can be reconstructed it needs to be first established that data can be identified as missing. Where few messages are present in a codeword there will naturally be large gaps between marks. For a given number of messages the probability of a gap is the probability of a series of consecutive zeros and can be determined from the Poisson distribution on the assumption that the hash function distributes evenly throughout the codeword. The probability of finding a block of empty marks of length \( E \) in a codeword of length \( C \) is:

\[ P_B = \frac{C-E}{C} P(0)^E \]  

Where \( P(0) \) is the Poisson probability of an empty mark obtained from:

\[ P(x) = \mu^{x} \frac{e^{-\mu}}{x!} \]  

The parameter \( \mu \) is the mean value which is the mark density of the codeword. For a given number of messages, \( m \), the mean value can be obtained from equation (4) as

\[ \mu = \frac{Z(m)}{C} \]  

The probability of a block of empty marks equivalent to 10% of the codeword size as a function of the number of encoded messages is shown in Figure 7. For only 5 messages this probability is 2% suggesting that missing data chunks can be reliably detected with a minimum of 5 messages. More messages makes smaller data gaps detectable, with a 5% gap having a probability of 0.3% with 20 messages encoded.

![Figure 7](image-url)  

Figure 7. The probability of a block of empty marks equating to 10% of the codeword size as a function of the number of encoded messages.
Data gaps were introduced into prepared codewords by zeroing contiguous chunks. In the decoding process received codewords were first examined to identify the presence of data gaps above a size threshold. Decoding branches whose marks would have appeared in the gaps were not discarded but retained and examined in the next decoding round. With a list of 30 random messages encoded, the decoding performance for different sizes of missing data chunks is shown in Figure 8. Perfect decoding with no hallucinations can be achieved with 30% of the codeword missing. Hallucinations begin to appear at 40% missing and increase rapidly as more codeword is removed. However even at 70% missing, the original messages can still be successfully received. This is remarkable robustness.

Figure 8. Decoding performance of a codeword containing 30 messages with various sizes of missing data cut out, shown as a percentage of the whole codeword. The left hand plot shows the hallucinations generated in the concurrent code scheme, the right hand plot shows the fraction of errors introduced into the original messages.

In comparison similar tests upon the Hamming interleaved coding behaved as one would expect. The interleaving spacing can in principle be large if the number of messages to be included is known by the receiver. However for concurrent coding the number of included messages can be variable and does not need to be known by the receiver to allow successful decoding. Therefore the only appropriate comparison for the HIC is to assume that the transmitter will interleave with a spacing given by the maximum available number of messages, and unused messages will just be zero padded. Hamming encoding of an 8 bit message gives a 16 bit result, thus there are 64 available messages and the codeword is interleaved into 16 sections. The Hamming encoding is capable of correcting 1 corrupted bit in each 4 bits of the original message. The original 8 bit message was broken into 2 chunks and the 16 bit Hamming encoded word created by appending the encoded bits. As interleaving spaces adjacent bits into neighbouring sections it would be possible for a gap of missing data greater than an interleaving spacing to corrupt 2 bits within a Hamming(8,4) encoding. Therefore the interleaving must be crossed between encodings such that an arrangement of word bits \( a_1a_2…a_{16},b_1b_2…b_{16}… \) is encoded as \( a_1b_1c_1…a_{8}b_{8}c_{8}…a_{2}b_{2}c_{2}… \). This ensures the maximum tolerance to data gaps is enacted. It follows that a missing section whose extent is larger than 2 interleaving distances will begin to corrupt the decoding, and an extent of 3 interleaving distances would usually corrupt all the messages. However in this implementation to ensure like-for-like comparison missing bits are replaced by zeros (as opposed to no data in some modulation schemes) which means that the scheme fails gracefully. The result of decoding performance with missing codeword chunks for the Hamming interleaver is shown in the right hand plot of Figure 8 where the fraction of errors in the decoded messages is given. It can clearly be seen that when the missing data cut out exceeds 2 interleaving spacings (12.5%) errors start to appear.
So an interleaver has a maximum size of intermittency that can be corrected, in this case 12.5% of the codeword after which messages become corrupted. In contrast concurrent coding has a minimum detectable intermittency, all messages are successfully decoded but are obscured by hallucinations.

**Reed Solomon Comparison**

What has been described here as intermittency in relation to signal connectivity, is perhaps more widely recognised as burst error correction. For this Reed Solomon (RS) encoding is an effective method for correcting symbol errors that can occur as a result of signal dropout [9], and hence some comparison with RS encoding is appropriate. The first comparison to draw is that concurrent codes only work with binary signals whereas RS codes operate with symbols and are therefore perhaps complimentary. RS encoding corrects for symbol errors irrespective of the number of bit errors in the symbol and it is the symbol error rate that determines the decoding fidelity, much as Concurrent Coding reconstructs messages. Whether a symbol contains 1 bit error or multiple bit errors makes no difference because whole symbols are corrected.

From Figure 8 it was established that a 30% signal loss can be corrected with good fidelity, where 10 bit messages contained 8 bits of data with a codeword length of 1024 bits. The equivalent RS code would be an R(128,98) where 128 represents the number of 8 bit symbols in the codeword space and 98 is the number of data symbols that can be encoded. However whilst a 30% dropout can be successfully reconstructed using an RS code, any additional noise would lead to symbol errors, whereas with concurrent code this will at worst lead to hallucinations.

The whole codeword space for RS encoding must be filled which is clearly not the case for concurrent coding as marks are only included representing messages and could therefore contain only a single message. Concurrent codes are therefore more efficient in terms of transmitted energy content. Indeed comparing with the RS(128,98) code, the equivalent concurrent code containing 100 messages would generate around 340 marks whereas the RS codeword would contain an equal number of 0’s and 1’s and therefore 512 marks. The RS code is therefore 50% less efficient than the equivalent concurrent code, which could be a significant benefit where low power usage is required.

**Modelling for Computational load**

Choosing the number of messages to include in a concurrent coding will depend upon factors such as the need for overcoming intermittency (a minimum number), the time taken to decode the codeword which increases computational load as the number of messages increases, and the effects of noise. A simple model for understanding the computational load can be understood as follows. Each round of decoding involves 2 calls to the hash function for every branch in the decoding tree that survives. The number of possible branches at each decoding round is \(2^i\) where \(i\) is the integer index of the decoding round and \(1 \leq i \leq N\). Assuming for simplicity that whilst \(2^i < m\) (the number of messages) all available branches are live, then when \(2^i > m\) hallucinations are created through the presence of noise. Each live branch can spawn 2 branches in the next round until the check sum bits are reached in which case branches can only be killed and not created. The number of live branches \(B_i\) at decoding round index \(i\) is given by:

\[
B_i = 2^i \text{ if } 2^i < m \\
\]

When the number of possible branches exceeds the number of messages present:

\[
B_i = m + (2^i - m)P_n^{-a+1} \text{ for } i > a
\]
Where \( a = \text{floor}(\log_2(m)) \) and \( P_n \) is the probability of each branch finding a mark arising from noise. This is given simply as the noise fraction, \( n \), the ratio of the number of noise marks to the codeword length. \( P_n = n = \text{Noise} / 2^n \). When the decoding process reaches the checksum bits the hallucinations are killed off and the number of live branches is:

\[
B_i = m + (2^b - m)P_n^{i-a+1} \text{ for } i > b
\]

(11)

Where \( b \) is the index at which \( k \) checksum bits are used, \( b = N - k \).

In Figure 9 the left hand plot shows the number of live branches at each round of the decoding process for various numbers of encoded messages and a noise fraction of \( n = 0.45 \). The right hand plot in Figure 9 shows the number of branches at each decoding round with 32 encoded messages and various noise levels. It can be seen that as \( 2^i > m \) the number of branches decreases as long as \( n < 0.5 \). After round 8 the checksum bits begin to kill branches. Note that this assumes a perfect hashing function with no clashes or interactions between messages. The computational load is simply the sum of the number of branches at each stage and is shown in Figure 10 for two noise levels.

The number of expected hallucinations is then calculated as:

\[
H = B_N - m
\]

(12)

Figure 9. The number of live branches at each round of the decoding process. The left hand plot shows the numbers of live branches for various numbers of messages encoded and a noise fraction of 0.45. The right hand plot shows the effects of noise upon the number of branches with each having 32 messages present.
Figure 10. The computational load for modest and high noise levels

Accounting for the effect of missing data in the form of contiguous gaps can be done as follows. It is assumed that the perfect hash function distributes marks randomly and evenly throughout the codeword, with no order relating to the bit position. Any branch leading to a mark that falls into an identified gap will be retained in the decoding process. The probability of this, given the assumptions of a perfect hash, is the ratio of the gap extent to the codeword size. This probability can be included into equations (9) and (10) as

\[ B_i = m + (2^i - m)(P_{n} + P_{g})^{i-a+1} \text{ for } i>a \]  

\[ B_i = m + (2^b - m)(P_{n} + P_{g})^{i-a+1} \text{ for } i>b \]

Where \( P_{g} = g = \text{gap} / 2^N \). Figure 11 shows a plot of the number of live branches for each decoding round for various sizes of gap present. The number of messages was kept constant at \( m=32 \) and the noise fraction was zero.

Figure 11. Live branches for differing gap size fractions. A constant number of message \( m=32 \) was used.
The predicted level of hallucinations is shown along with measured hallucination levels in Figure 12. At high levels of missing data this underestimates the number of hallucinations. This is most likely due to the PRBS algorithm being an imperfect hash function. Both distributions show good agreement in where hallucinations start to be produced. The threshold for hallucination production can be determined using equations (12) and (14) by setting \( H=1 \) and assuming \( n=0 \):

\[
g_t = \left( \frac{1}{2^b - m} \right)^{N-a+1}
\]

Using values from Figure 12 with \( m=32, N=10, a=5, b=8 \), this gives a threshold value of \( g_t=0.4 \), which is in good agreement with the data plotted in Figure 12.

Setting the gap fraction to zero the same calculation gives the threshold at which noise starts to generate hallucinations. This value of \( n_t=0.4 \) corresponds to 16dB, in reasonable agreement with the measured data plotted in Figure 4. It seems likely then that a concurrent code has an inherent tolerance for a combination of gaps and noise as both contributions are additive in their effect upon the probability of generating hallucinations.

**Extensions**

Concurrent coding is efficient because messages with the same sub sequence will share marks in the codeword. This can be seen in the nonlinear relationship between the number of messages and the number of marks as shown in Figure 6. Whilst many messages can be overlaid into the codeword through a common hashing function, this does mean that any message can only appear once in any codeword, which could be inconvenient for practical applications. It is also not clear that any particular order for the messages can be maintained through the decoding process, thus requiring the receiver to make sense of the decoded messages. What is required is therefore some method for including additional information about the contents. This could be done through selective use of special or handshaking messages. However another possibility is to encode several sets of messages using different hashing functions. This would allow a set of control messages to be overlaid upon the data messages. This would also allow the same messages to be included several
times in the same codeword. This is of course a less efficient way of encoding the information as multiple use of marks is less likely and would increase the computational load in comparison to the same number of messages with one hash function. An initial trial of this approach was attempted using PRBS hash functions with different initial states. A set of messages was encoded several times using different hash states. It was found that with 2 hash states the message lists could be correctly decoded, each showing the same values. More hash states resulted in the generation of hallucinations which suggests there is a significant interaction between PRBS functions. Additionally the PRBS hash function was modified to provide several versions with different internal feedback connections representing different hash functions. This however generated hallucinations when more than one hash function was used. It seems clear that the principle is sound but requires the use of non-interacting hash functions to be effective. This should be the subject of future investigations.

Conclusions
Concurrent codes offer a useful alternative to established encoding methods where robustness to noise and intermittency is required. This work has shown that a simple approach to keep down complexity and computational burden by using small messages and a PRBS can offer remarkable resilience to noise and intermittency. It has been shown that with contiguous chunks of missing data of a size greater than 30% of the total transmitted data, the whole transmission can be recovered with perfect accuracy. This resilience to data intermittency can be achieved without the use of cyclic codes or interleaving. The use of indelible marks (an asymmetric binary code) means that the original data encoded into the transmission can always be recovered although sometimes obscured by false decodings. Thus, even with in excess of 50% of the encoded transmission removed the original data was still received and decoded. This remarkable facility takes the use of concurrent codes well beyond the original remit of providing resistance to jamming without the use of a shared encryption key. This technique could be used in situations where it is vitally important that specific transmitted information is received, such as hostile military scenarios or the conveyance of medical or security information. Information conveyance through harsh and noisy environments could be implemented. Of particular relevance are situations where transmissions are subject to random intermittency such as free space optical communications where atmospheric scintillation can cause beam wander away from a receiver, or line of sight can be interrupted by moving vehicles. In such circumstances it is important to match the intermittency time to the codeword length to ensure correct reconstruction of the data. Equally so with rapid RF fading.

The requirement for the use of indelible marks aligns well with on-off keying modulation. Where power is only emitted for the 1’s within the data, concurrent coding is significantly more efficient than other encoding schemes and would therefore be well suited to applications that require reduced power transmission, either to preserve stored power or to reduce the probability of signal interception.

Whilst it is certainly true that cyclic codes such as Reed Solomon encoding coupled with interleaving can offer a significant correction to burst errors and data corruption, there is value in an approach that is significantly simpler to understand. Concurrent codes are fundamentally different to cyclic codes and interleaving in the following ways: 1) they do not require additional data to be merged with the original through an encoding that records the parity.2) concurrent codes do not lose data when the corruption exceeds the capacity of the code to correct errors. 3) the decoding of concurrent codes is likely to be more computationally intensive than decoding of cyclic codes.

Clearly there is scope for more investigation into the design and application of concurrent codes with respect to code lengths, hashing functions, security concerns and interwoven data.
References:

[1]. Baird, Leemon C. III, Bahn, William L. & Collins, Michael D. (2007) Jam-Resistant Communication Without Shared Secrets Through the Use of Concurrent Codes, Technical Report, U. S. Air Force Academy, USAFA-TR-2007-01, Feb 14.

[2]. Baird, Leemon C. III, Bahn, William L., Collins, Michael D., Carlisle, Martin C. & Butler, Sean (2007) "Keyless jam resistance", Proceedings of the 8th Annual IEEE SMC Information Assurance Workshop (IAW), Orlando, Florida, June 20-22, pages 143-150.

[3]. Bahn, William L., Baird, Leemon C. III & Collins, Michael, D. (2008) "Jam resistant communications without shared secrets", Proceedings of the 3rd International Conference on Information Warfare and Security (ICIW08), Omaha, Nebraska, April 24-25.

[4]. Baird, Leemon C. III, Carlisle, Martin & Bahn, William L (2010) "Unkeyed Jam Resistance 300 Times Faster: The Inchworm Hash", MILCOM 2010 - Military Communications Conference, San Jose, CA, Oct

[5]. Baird, Leemon C III, Schweitzer, Dino, Bahn, William L & Sambasivam, Samuel (2010) "A Novel "Visual Cryptography" Coding System for Jam Resistant Communications", Journal of Issues in Informing Science and Information Technology, 7, pages 495-507.

[6]. Viterbi, A J "Error bounds for convolutional codes and an asymptotically optimum decoding algorithm". IEEE Transactions on Information Theory 13 (2): 260–269. (1967).

[7]. Berrou, C., Glavieux, A., & Thitimajshima, P. (1993, May). Near Shannon limit error-correcting coding and decoding: Turbo-codes. 1. In Communications, 1993. ICC 93. Geneva. Technical Program, Conference Record, IEEE International Conference on (Vol. 2, pp. 1064-1070). IEEE.

[8]. Baird, L. C., Carlisle, M. C., Bahn, W. L., & Smith, E. (2012, October). The Glowworm hash: Increased speed and security for BBC unkeyed jam resistance. In military communications conference, 2012-milcom 2012 (pp. 1-6). IEEE.

[9]. Sklar B, Digital Communications: Fundamentals and Applications, Second Edition (Prentice-Hall, 2001, ISBN 0-13-084788-7).