Novel Implementation of a Keyless Concurrent Codes Spread-Spectrum (CCSS) Jam-Resistant Method in GNU Radio

Abstract—Current omnidirectional jam-resistant technology relies on shared secrets. This forces private networks to exchange keys before jamming is present and leaves public networks (like GPS or ADSB/Mode-S) unprotected. Given the proliferation of inexpensive Software Defined Radios (SDRs), robust jam-resistant options are more important than ever. This project implements the “BBC” codec—a keyless, concurrent codes spread-spectrum (CCSS) strategy—in GNU Radio. Initial testing of the BBC codec confirms theoretical performance estimates and suggests that BBC is a viable option to preserve information availability. Development is underway to provide an out-of-tree (OOT) module for broader use within the GNU Radio community.

Keywords—concurrent codes, jam-resistant, wireless, RF, communications, BBC, GNU Radio, SDR

I. BACKGROUND

Modems that support protected (i.e., private) omnidirectional wireless connections leverage keys for two primary functions: Traffic Encryption Keys (TEKs) protect the content of traffic, while Transmission Security Keys (TSKs) protect the physical-layer signal. Historically, these keys were all symmetric, having to be exchanged in advance under ideal conditions. Thus, protected networks—especially those relying on omnidirectional broadcasts—had frustrating scalability and use-case limitations. However, the advent of asymmetric keys and Public Key Infrastructure (PKI) allowed public keys to be sent without concern, effectively solving the key-sharing problem for TEKs. Even the low bit-rates of asymmetric algorithms such as Diffie-Hellman key exchange and RSA have been outperformed by hybrid approaches where symmetric keys are shared during an asymmetrically-keyed connection, allowing higher-rate symmetric algorithms like 3DES and AES to encrypt sustained connections. [1]

Despite these advancements, protected connections are still contingent on symmetric TSKs for jam-resistance. That is, asymmetric keys fail to facilitate modern omnidirectional transmission security strategies like frequency-hopping spread spectrum (FHSS), direct-sequence spread spectrum (DSSS), and time-permutation. Thus, protected networks still have scalability and use concerns. After careful, yet prolonged distribution of symmetric TEKs, it is likely that one or more keys may become compromised. With a compromised TEK, a TSK transmitted at the beginning of a broadcast may be intercepted. As a result, the signal may be jammed in the physical layer, even if the TEK encryption holds. This danger is exacerbated because the difficulty of key-redistribution grows with the size of the network. Furthermore, without a TSK’s physical-layer advantages, encrypted connections cannot exchange a TSK when jamming is present. Such a broadcast is susceptible to degradation or even denial.

Furthermore, public networks (i.e., those without an enumerated list of authorized users) cannot leverage symmetrically-keyed jam-resistance. Since, in effect, everyone has the TSK, adversaries could predict the spectrum usage of the signal and easily jam it. As the technology industry’s reliance on large-scale networks like Global Navigation Satellite Systems grows, jam-resistance becomes increasingly crucial to preserve proper functionality.

The communications community has been making efforts toward these ends. In [2], Pöpper, Strasser, and Čapkun were able to achieve linear time complexity with Uncoordinated Direct-Sequence Spread Spectrum (UDSSS), which did not rely on shared secrets. However, this strategy required a delay between the message transmission and the jamming transmission to establish physical-layer jam-resistance. Though this is a robust methodology for many use-cases, the ability to establish a connection under adverse conditions has yet to be demonstrated.
II. BBC ALGORITHM

As proposed by Baird, Bahn, and Collins, the BBC codec is a physical-layer solution for keyless jam-resistant communication, with no inherent requirement for an uncontested synchronization step [3]. By modeling the wireless channel as a bitwise-OR, BBC leverages the fact that, though jamming adds unwanted information to transmitted codewords, it is unable to remove information that is already there (i.e., bits with value 1). Given that the bitwise-OR is a good approximation for some variable-envelope asymmetric modulation schemes, it is useful to represent a signal as a bit vector. This simplification does not describe a signal’s power distribution across frequency and time (or its phase) but is a useful heuristic and may be implemented by diverse modulation strategies.

A BBC "mark" is a binary 1 that serves as a marker for a specific substring, and a packet is a bitwise-OR of a transmitted codeword and any additional marks from intentional or unintentional interference. After receiving a packet, a decoder may do two things: it may decode the packet as a single message or it may decode every message covered by the packet. In the former case, a transmitter and receiver pair that use a codec which encodes characters as ASCII may send a ‘2’ across an intentionally or unintentionally jammed channel and receive a ‘3’. Thus, the packet has been corrupted by the addition of a single 1 in the codeword:

<table>
<thead>
<tr>
<th>Origin</th>
<th>ASCII Character</th>
<th>ASCII Byte (Codeword)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original message (TX)</td>
<td>2</td>
<td>00110010</td>
</tr>
<tr>
<td>Jamming signal</td>
<td>1</td>
<td>00100001</td>
</tr>
<tr>
<td>Channel packet (OR)</td>
<td>3</td>
<td>00110011</td>
</tr>
<tr>
<td>Decoder (RX)</td>
<td>3</td>
<td>00110011</td>
</tr>
</tbody>
</table>

In the latter case, the decoder reverses the channel bitwise-OR by decoding every possibility. Using the above example, the output of the decoder includes the original message and many “hallucinations.”

Even after filtering for characters (i.e., ASCII bytes which are between the decimal values 32 and 126 inclusive), there are 7 incorrect messages, or “hallucinations”; 87.5% of the decoded packet is erroneous. Evidently, the computational efficiency of the decoder drops as more codewords are covered by the packet—that is, as there are more 1s than 0s in the packet. Furthermore, consistently selecting the original message from the hallucinations is impractical.

This toy example informs the primary goal of the BBC codec: to reduce the number of hallucinations introduced by a bitwise-OR of its codewords. Toward this end, BBC

<table>
<thead>
<tr>
<th>Message substring</th>
<th>Mark index from hash</th>
<th>Codeword after placing mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘0’</td>
<td>5</td>
<td>00000010 00000000</td>
</tr>
<tr>
<td>‘00’</td>
<td>0</td>
<td>10000000 00000000</td>
</tr>
<tr>
<td>‘001’</td>
<td>14</td>
<td>10000001 00000000</td>
</tr>
<tr>
<td>‘0011’</td>
<td>2</td>
<td>10100000 00000000</td>
</tr>
<tr>
<td>‘00110’</td>
<td>0</td>
<td>10100001 00000000</td>
</tr>
<tr>
<td>‘001100’</td>
<td>0</td>
<td>10101000 00000000</td>
</tr>
<tr>
<td>‘0011001’</td>
<td>1</td>
<td>10110001 00000000</td>
</tr>
<tr>
<td>‘00110010’</td>
<td>12</td>
<td>10110100 00000010</td>
</tr>
</tbody>
</table>

Though indices for 8 marks have been generated by the hash function, 3 of the substrings’ mark indices were
the same: 0. This overlap suggests that the arbitrary length of $2n = 2^8 = 16$ bits may be too small; the codeword density, $\mu$, is approaching the limit of the decoder. Since there are 6 marks and 16 bits in the codeword, $\mu = \frac{6}{16} = 0.375$. The receiver codec will still decode the packet in linear time since the codeword density is under 0.5 \[1\]. However, there likely will be hallucinations.

To reverse the encoder’s mark placement, the decoder must rebuild every message that may have been included by checking for marks corresponding to various substrings. In the case of a small 16-bit codeword, there are $2^{16} = 65536$ message possibilities. A depth-first search tree is employed to check for substring marks in the codeword efficiently. That is, the decoder begins by proposing that the message began with ‘0’. If there is a mark in the codeword corresponding to the substring ‘0’, this branch is taken and ‘00’ is tested. If not, the decoder tests for the substring ‘1’, and so on. Below is the decoding tree for the 16-bit BBC codeword for ASCII ‘2’, 1001110000001010.

![Decoder Tree](image)

### TABLE IV
<table>
<thead>
<tr>
<th>Channel OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin ASCII Character</td>
</tr>
<tr>
<td>Original message (TX) 2</td>
</tr>
<tr>
<td>Jamming signal !</td>
</tr>
<tr>
<td>Channel packet (OR) N/A</td>
</tr>
</tbody>
</table>

Now over the 0.5 packet density threshold, the decoder returns 14 possibilities (8 of which are ASCII characters)—a comparable result to the ASCII-only encoder. This example demonstrates the importance of judiciously sizing the BBC codeword. In the same jamming scenario, the decoder finds 5 message possibilities if a 32-bit codeword is used. With a 56-bit codeword, no hallucinations are present: only ‘2’ and ‘!’ remain.

### III. THE GLOWWORM HASH

In \[4\], Baird, Bahn, Carlisle, and Smith designed a hash to optimally place marks and reduce overlap. This "Glowworm" hash was originally written as C macro functions but has been translated to Python to support object-oriented integration in GNU Radio. This hash is comprised of 3 functions: one for initializing a shift register, one to process a bit and return a mark index, and one to restore the shift register’s state after processing a bit (i.e., a bit deletion). The \texttt{init()} function fills up a shift register with 32 64-bit words. The initial hash state is determined by 4096 iterations of adding the previous entry’s least significant bit.

```python
# Initialize Glowworm

def init(s):
    n = 0
    h = 1
    for i in range(32):
        s[i] = 0
    for i in range(4096):
        h = add_bit(h & 1, s)
    n = 0

```

![Glowworm Initialization Function](image)

The \texttt{add_bit()} function actually hashes a given bit. In BBC, the modulo of its 64-bit return and the codeword length becomes the index of the new mark. In order to "hash a substring," each individual bit needs to be hashed in order. The shift register’s modified state is responsible for ‘01’ giving a different output than ‘1’ or ‘001’; it can essentially store a substring even though it is passed via
n separate function calls, where n is the length of the current substring and a global variable.

```python
# Enforce 64-bit word
MAX_VAL = 0xffffffffffffffff

# Hash a bit
def add_bit(b, s):
    t = (s[n % 32] ^ (0xffffffff if b else 0))
    t = ((t | (t>>1))^((t<<1)&MAX_VAL))
    t = (t ^ (t>>4)^((t>>8)^((t>>16)^((t>>32))))
    n += 1
    s[n % 32] ^= (t&MAX_VAL)
    return s[n % 32]

# Unhash a bit
def del_bit(b, s):
    n -= 1
    add_bit(b, s),
    n -= 1
    return s[n % 32]
```

Fig. 3. Glowworm Hash Function

Finally, the `del_bit()` function reverses a hash state change caused by `add_bit()`. This enables the BBC decoder to navigate the search tree; in cases where a substring’s mark is not found in the codeword, `del_bit()` unhashes the last bit and traverses one level up in the tree.

```python
def del_bit(b, s):
    n -= 1
    add_bit(b, s),
    n -= 1
    return s[n % 32]
```

Fig. 4. Glowworm Reverse Hash Function

IV. IMPLEMENTATION OF BBC IN PYTHON

Python’s support of object oriented programming enables the creation of a BBC codec object that can simultaneously encode messages and decode codewords. This is advantageous toward supporting full duplex wireless communication, rather than relying on procedural scripts. Furthermore, Python’s built-in bytearray object supports a variable-length array that can store more information than a machine-precise 64-bit word. This is particularly helpful for creating large codewords (e.g., \(2^{20}\) bits long). Since the bytearray object supports indexing via the `memoryview()` method, it is easy to place and search for BBC marks. The Python `Codec` object initializes both an `Encoder` and a `Decoder` for predetermined message, codeword, and checksum lengths (Appendix A.1). Note that BBC performs a pseudo-checksum by appending additional zeros to the message before encoding it, reducing the number of hallucinations contained in the codeword.

To create a BBC codeword, data is parsed from the source, interpolated to `message_length`-long bit vectors, and passed to the `Encoder` (Appendix A.2). Once its Glowworm shift register has been initialized (lines 11-14), it is free to iteratively place marks for each substring in the message (lines 27-34). Only one bit is hashed at a time, but the shift register stores the rest of the substring until bits are deleted from it.

To decode a BBC codeword, an iterative model is used, rather than the recursive model proposed in [1]. This novel approach increases efficiency and reduces the stack size, making it computationally easier to decode larger packets/codewords. Messages that have a mark in the codeword for each substring are stored in the static variable, `message_list` (Appendix A.3).

To iterate the depth-first search, the decoder uses Glowworm to check if it can append a ‘0’ to the current message substring, which is initially empty. If Glowworm returns an index where a mark is present in the codeword, the current substring is valid, and the “explore” path is taken (lines 33-48). If the current substring is not covered by the packet, then the "backtrace" path is taken (lines 51-72). Here, the algorithm can reliably take the next “deepest” path by deleting ‘1’s from the end of the current message substring until a ‘0’ is encountered (reducing its depth), at which point it changes that ‘0’ to a ‘1’ and continues to the next iteration. After every message covered message is found, they are all returned via `message_list` (Appendix A.3, line 75).

V. IMPLEMENTATION OF BBC IN GNU RADIO

To facilitate SDR testing with GNU Radio, the `Encoder` and `Decoder` are implemented as synchronous and interpolating Python Blocks, respectively (Appendices B.2-B.3). Each has a `blk` constructor that instantiates the respective python class, enabling the `work` method to call BBC functions. Since the message and codeword lengths must be pre-determined and consistent between encoder and decoder, they are defined as top-level variables in the flowgraph (Appendix B.1). Stream-to-vector and vector-to-stream blocks manage the data flow appropriately.

Adjusting these top-level variables, however, currently causes a compilation error. GNU Radio does not yet support dynamic argument assignment inside the python block constructor. That is, the actual values of the top-level variable are ignored in favor of the corresponding default arguments. As a result, the message and codeword lengths had to be hard-coded in both blocks each time a different configuration was desired. This is still an open issue in the core GNU Radio source code, with a partial work-around in [5].

Initial verification consisted of a simulation (Appendix C.1). This test demonstrated the BBC codec’s ability to encode multiple messages into a single codeword (i.e., a “packet”) and recover both. In GNU Radio, two encoder blocks each encoded a message. The resulting codewords were passed to a native “OR,” which simulated the
channel. Both messages were decoded from the packet with no hallucinations.

Furthermore, the recommended 50% packet density limit was validated with two separate tests in GNU Radio. First, using a \( (2^{10}) \) bit message (128 bytes), codeword lengths were varied from \( 2^{20} \) down to \( 2^{11} \) bits [3]. At \( 2^{11} \) bits, the codeword was twice the size of the message, and thus had an expected codeword density of 50%. As predicted, the decoder broke exceeded linear time and produced many hallucinations.

Second, the simulation was used to investigate the effect of extra marks on the decoded messages (Appendix C.2). In this test, a single byte mask was OR’d with each byte of the codeword, producing a variable number of extra marks. As expected, byte masks which contained three 1’s (such as the 00011010\( ^2 \)) did not significantly affect the decoding process, since the packet density was still below the 50% threshold. However, 4-bit-high masks such as 00110112 = 27\( ^{10} \) produced a failure in the decoder.

Testing showed that a significant codeword-to-message ratio (such as \( 2^{10} \)) made the BBC codec resistant to a significant amount of bit-errors induced by jamming or noise. Choosing a large codeword forces the original codeword density to be low, enabling robustness against a significant number of erroneous marks.

### VI. USE CASE VERIFICATION

The next logical step is to incorporate the BBC encoder/decoder framework into a representative modulation scheme. In [1], Bahn advises against using BBC in conjunction with any constant-envelope methods, because they allow added power to erase marks, invalidating the bitwise-OR assumption. That is, noise or jamming could theoretically remove a mark. Therefore, we selected on-off-keying (OOK) selected for an initial test-case (Appendices C.3-C.4).

The OOK codec and modulation/demodulation process was relatively straightforward and uses bitwise modulation of a cosine carrier. For simplicity’s sake, we saved the modulator and demodulator as hierarchical blocks. Note that the BBC codec is modulated, not the individual messages.

In order to assess the performance of the BBC OOK implementation, the transmission time was compared with an OOK simulation containing no BBC blocks and using the OOK decoder hier block to transmit a \( 2^{20} \) bit codeword. The difference in performance between the two execution times was negligible, providing reasonable confirmation of the codec’s efficiency. In fact, the decoder run time was approximately 20ms, a negligible portion of the flowgraph run time.

One possible use case of the BBC codec is to facilitate key (or key parameter) sharing for another communications protocol that may be more secure and higher bandwidth, in the presence of jamming or noise. Therefore, in the flowgraph contained in Appendix C.5, frequency hopping parameters are passed through the BBC OOK transmitter and the output commands the FHSS hop sequence. In this simple case, two frequencies are sent in a single codeword, but, with a sufficiently large codeword, a large number of frequencies could be passed – essentially constituting a hop table. This flowgraph provides a proof-of-concept for a very real use case incorporating BBC communications.

### VII. CONCLUSIONS AND FUTURE WORK

More work is needed to develop the robustness of and specify the use-cases for BBC. First, there are theoretical performance upgrades to the base algorithm. These include multimark BBC, codeword detection, and automatic gain control [3]. Multimark BBC reduces the number of hallucinations in a decoded packet by requiring each substring to have more than 1 associated mark. This comes at a cost, though: the addition of more marks may force the receiving decoder beyond the 50% packet density threshold. Codeword detection would enable BBC packet lengths to be greater than the selected codeword length; this is a necessary step to implement the encoder and decoder on separate clocks. Finally, automatic gain control would allow a receiver with a BBC decoder to operate in noisier environments. By adjusting the power threshold that separates the 0 and 1 symbols, the decoder could ensure that it remains below the 50% packet density threshold.

Second, statistical modeling would help specify the BBC use case. Predicted performance metrics would inform message, codeword, and checksum length selection for variable data-rates and expected jamming/noise powers. Specific to the encoder, these metrics include codeword density and overlap count, as functions of codeword and message lengths. For the decoder, they include expected packet density and decode time-complexity, as functions of codeword and message lengths and expected channel noise (Note that the ratio of message length to codeword length is a useful approximation for packet density but technically is incorrect due to mark overlaps).

Finally, rigorous and thorough testing of BBC under diverse noise and jamming strategies must be conducted to prove the algorithm’s worth in any real-world use case. Reducing the probability of mark-deletion necessarily increases the probability that an erroneous mark is added, and the bit-error probabilities for BBC with OOK or other modulation strategies have not been tested.

Shortly, an OOT module will be released via github/C-GRAN, BBC will available for widespread use and development.
REFERENCES


A.1 Codec Class

```python
class Codec:
    # The codec is comprised of an encoder and decoder, with an associated message/codeword pair
    def __init__(self, MSG_LEN, COD_LEN, CHK_LEN):
        self.MSG_LEN = MSG_LEN
        self.COD_LEN = COD_LEN
        self.CHK_LEN = CHK_LEN
        self.encoder = Encoder(self.MSG_LEN, self.COD_LEN, self.CHK_LEN)
        self.decoder = Decoder(self.MSG_LEN, self.COD_LEN, self.CHK_LEN)

    def bbc_encode(self, message):
        self.encoder = Encoder(self.MSG_LEN, self.COD_LEN, self.CHK_LEN)
        return self.encoder.encode(message)

    def bbc_decode(self, codeword):
        self.decoder = Decoder(self.MSG_LEN, self.COD_LEN, self.CHK_LEN)
        return self.decoder.decode(codeword)
```

A.2 Encoder Class

```python
import glowworm.py as gw

class Encoder:
    def __init__(self, MSG_LEN, COD_LEN, CHK_LEN):
        self.shift_register = self.init_shift_register()
        self.MSG_LEN = MSG_LEN
        self.COD_LEN = COD_LEN
        self.CHK_LEN = CHK_LEN

    def init_shift_register(self):
        shift_register = [0 for i in range(32)]
        gw.init(shift_register)
        return shift_register

    def parse_input(self, input):
        input = input.encode(encoding="ASCII")
        message = bytearray(int(self.MSG_LEN/8))
        memoryview(message)[0:len(input)] = input
        return message

    def encode(self, input):
        message = self.parse_input(input)
        codeword = bytearray(int(self.COD_LEN/8))
        for i in range(self.MSG_LEN):
            # ASCII byte to be encoded
            element = memoryview(message)[int((i-i%8)/8)]
            bit = ((element) >> (i%8)) & 0b1
            # Extract bit from Byte
            mark_loc = gw.add_bit(bit, self.shift_register) % self.COD_LEN
            # Mark location from glowworm
            memoryview(codeword)[int((mark_loc-mark_loc%8)/8)] |= 1<<(mark_loc%8)
        return codeword
```
from math import ceil
import glowworm.py as gw

class Decoder:
    # Store configuration parameters as static variables
    def __init__(self, MSG_LEN, COD_LEN, CHK_LEN):
        # <Constructor here>

    # Allocate memory for and initialize the shift register
    def init_shift_register(self):
        shift_register = [0 for i in range(32)]
        gw.init(shift_register)
        return (shift_register)

    # Use novel iterative approach to decoding a packet
    def decode(self, packet):
        # Initialize variables
        self.message_list = []
        message = bytearray(ceil((self.MSG_LEN + self.CHK_LEN)/8))

        while True:
            # Find the proposed bit from previous execution, or a 0 if initial iteration
            prop_bit = (memoryview(message)[int((self.n - self.n%8)/8)]>>(self.n%8)) & 0b1

            # Find the corresponding mark location from glowworm
            val = gw.add_bit(prop_bit, self.shift_register) % (self.COD_LEN)

            # Logical AND to determine if present in packet/codeword
            bit = (memoryview(packet)[int((val-val%8)/8)]>>(val%8)) & 0b1

            # If the mark is present, explore
            if bit==1:
                # Message is complete, write to buffer
                if self.n == (self.MSG_LEN + self.CHK_LEN - 1):
                    self.message_list.append(bytes(memoryview(message)[0:self.MSG_LEN - 1 - self.CHK_LEN]))
                    bit = 0

            # Message is incomplete, continue assuming next bit is 0
            elif self.n < (self.MSG_LEN + self.CHK_LEN - 1):
                self.n += 1
                memoryview(message)[int((self.n - self.n%8)/8)] &= (0xff ^ (1<<self.n%8))
                continue

            # If the mark is not present, backtrace
            if bit!=1:
                # Delete checksum bits
                while self.n >= self.MSG_LEN:
                    gw.del_bit(0, self.shift_register)
                    self.n -= 1

                # Delete 1's until a 0 is encountered
                while self.n >0 and (((memoryview(message)[int((self.n - self.n%8)/8)]>>
                    (self.n%8)) & 0b1 )==1):
                    gw.del_bit(1, self.shift_register)
                    memoryview(message)[int((self.n - self.n%8)/8)] &= (0xff ^ (1<<self.n%8))
                    self.n -= 1

            # Packet is fully decoded, proceed with next packet
            if self.n < 0:
                break

        # Move over to the 1 branch of current search
        else:
            gw.del_bit(0, self.shift_register)
            memoryview(message)[int((self.n - self.n%8)/8)] |= (1<<self.n%8)

        return self.message_list
APPENDIX B
GNU RADIO IMPLEMENTATION

B.1 Top-Level Chart

B.2 GNU Radio Encoder Block Class

```python
from gnuradio import gr
import numpy as np

class blk(gr.sync_block):
    # Configure port sizes
    def __init__(self, MESSAGE_LENGTH=2**7, CODEWORD_LENGTH=2**17):
        self.msg_len = MESSAGE_LENGTH
        self.cod_len = CODEWORD_LENGTH

        # Use a synchronous block
        gr.sync_block.__init__(self,
            name='BBC Encoder',
            in_sig=[(np.byte, self.msg_len)],
            out_sig=[(np.byte, self.cod_len)])

        # Convert from Bytes to bits
        self.myEncoder = Encoder(self.msg_len*8, self.cod_len*8)

    # Use BBC to encode the incoming message vectors
    def work(self, input_items, output_items):
        try:
            output_items[0] = self.myEncoder.encode(input_items[0])
            return len(output_items[0])
        except:
            raise RuntimeError("BBC Encoder output assignment failed")
```

B.3 GNU Radio Decoder Block Class

```python
from gnuradio import gr
import numpy as np

class blk(gr.interp_block):
    
    # Configure port sizes
    def __init__(self, MESSAGE_LENGTH=2**7, CODEWORD_LENGTH=2**17):
        self.msg_len = MESSAGE_LENGTH
        self.cod_len = CODEWORD_LENGTH

        # Use an interpolation block
        gr.sync_block.__init__(self,
                               name='BBC Decoder',
                               in_sig =[(np.byte, self.cod_len)],
                               out_sig =[(np.byte, self.msg_len)])

        # Initialize the interpolation rate to synchronous case
        self.set_relative_rate(1)

        # Convert from Bytes to bits
        self.myDecoder = Decoder(self.msg_len*8, self.cod_len*8, DEFAULT_CHECKSUM)

    # Use BBC to decode the incoming codeword vectors
    def work(self, input_items, output_items):
        # Pull packet from the queue
        packet = input_items[0][:][0]

        # Check for a nonzero codeword
        if sum(packet >0):
            result = self.myDecoder.decode(packet)
            interp = len(result)

            # Check for a decoded message
            if interp > 0:
                # Define the number of outputs
                self.set_relative_rate(interp)

                # Assign outputs iteratively
                for j in range(interp):
                    try:
                        output_items[0][j][:] = result[j]
                    except:
                        raise RuntimeError("BBC Encoder output assignment failed")

        return len(output_items)
```
C.1 Multi-Codeword BBC

C.2 Noise Injection
C.3 BBC with On-Off Keying

Variable
- ID: CODEWORD_LENGTH
- Value: 1.0

Variable
- ID: MESSAGE_LENGTH
- Value: 128

Variable
- ID: samp_rate
- Value: 128k

Variable
- ID: symbol_rate
- Value: 500

Variable
- ID: carrier_freq
- Value: 433.927M

Vector Source
- ID: message
- Value: HELLO WORLD!
- Tags: hi
- Repeat: no

Throttle
- Sample Rate: 128k

BBC Encoder

Vector to Stream

Virtual Source
- Stream ID: t_x

OOM Demodulator
- samp_rate: 128k
- symbol_rate: 500

Stream to Vector

BBC Decoder

Vector to Stream

Param Source Label: int

Pad Source

Pad Sink Label: int

C.4 On-Off Keying Modulator and Demodulator

Variable
- ID: bits_per_palette
- Value: 0

Parameter
- ID: samp_rate
- Value: 128k

Parameter
- ID: symbol_rate
- Value: 500

Parameter
- ID: carrier_freq
- Value: 433.927M

Signal Source
- Sample Rate: 128k
- Wavelength: 5.2GHz
- Amplitude: 1
- Initial Phase (Radians): 0

Pad Source Label: int

Band Pass Filter
- Decimation: 1
- Gate: 1
- Sample Rate: 128k
- Low Cut Off Freq: 50Hz
- High Cut Off Freq: 50KHz
- Transition Width: 5kHz
- Window: Hamming
- Beta: 6.76

Threshold
- Low IMF: 1
- Initial State: 0

Keep 1 in N

Float To Char

Unpacked to Packed Bits per Chunk: 1
Endianness: HDS
C.5 BBC-FHSS Seeding