

Q-Reduct

Quantum-Ready Erasure Codec for Extreme Storage Reduction

David N. Halenta

Picyboo Cybernetics Inc., Research Lab (Canada)

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Contact: desk@davidhalenta.de / contact@picyboo.com

CSR: <https://CognitiveScienceResearch.com/CSR4812>

ORCID: <https://orcid.org/0009-0003-3994-7912>

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Abstract

Q-Reduct is a lossless, quantum-ready erasure codec that achieves file-size reduction by deliberately discarding payload bits and retaining a compact set of deterministic constraints that uniquely characterize the original. Decoding is posed as an oracle-search problem: given the stored constraints, find the erased bits that make every local and global check true. Classically, aggressive erasure makes decoding computationally infeasible; on a future quantum computer, amplitude-amplification (Grover-style) reduces the expected search cost from $O(2^m)$ to $O(2^{(m/2)})$ oracle calls, where m is the effective constraint strength.

Keywords: quantum decoding, Grover search, oracular reconstruction, erasure codec, Merkle verification, linear syndromes, storage reduction

Projected benefit. Under quantum decoding and suitable parameterization, the size reduction approaches the erased fraction $e = d/k$ per chunk. With overhead amortized, reductions on the order of 80-90% (i.e., encoded size $\leq 10\text{-}20\%$ of original) are mathematically achievable for large e (e.g., $e \approx 0.9$) provided the quantum oracle budget suffices to search the induced space and the constraint set enforces uniqueness. Classically, the same parameters are intentionally impractical; small, testable settings validate correctness but do not exceed top classical compressors on average data.

Contributions. We specify the format, constraints, oracle, and verification hierarchy; derive classical vs quantum complexity; give parameter guidance; provide reference pseudocode and a PHP skeleton; and outline a rigorous evaluation plan and a quantum implementation roadmap.

1. Motivation and Scope

Modern compressors are close to Shannon-style limits on many corpora. Surpassing them consistently and losslessly requires adding information (side-info/models) or trading compute for storage. Q-Reduct formalizes the latter: remove bits now, prove uniqueness by constraints, and shift the heavy work to the decoder. The approach is:

- **Lossless by specification.** If decoding succeeds, the output equals the original bit-for-bit.
- **Asymmetric.** Encoding is linear-time; decoding cost scales with the constraint budget, not with encoder effort.
- **Quantum-ready.** The decoding predicate is an explicit oracle suitable for amplitude amplification.

Use cases. Long-horizon archives expecting quantum resources; controlled pipelines willing to accept expensive, delayed decode; research platforms evaluating quantum advantage on real data paths.

Non-goals. Q-Reduct is not a universal, faster-than-zstd drop-in today; it is a storage primitive whose practical advantage manifests only with quantum search (or vast classical compute) at aggressive settings.

2. Model and Notation

- **File size:** N bytes
- **Chunk size:** k bytes (fixed; last chunk may be shorter)
- **Erasure per chunk:** d bytes removed; prefix kept: $(k - d)$ bytes
- **Erasure fraction:** $e = d/k$
- **Chunks:** $C = \lceil N/k \rceil$
- **Candidate space per chunk:** $|S| = 2^{(8d)}$
- **Constraints per chunk:**
 - Digest m bits: $\text{dig}_i = \text{trunc}_m(H(\text{seed} \parallel \text{chunk}_i))$
 - Linear syndrome r bits: $s_i = H_{\text{lin}} \cdot v_i$ over GF(2)
 - Chain check t bits across neighbors
- **Global checks:** Merkle root over chunk digests; SHA-256 of the full original
- **Seed:** derived from a stable snapshot (e.g., filename hash, original size, original mtime) and/or a user passphrase

3. High-Level Architecture

Encoding.

Split the file into chunks of size k . For chunk i ,

store the prefix $P_i \in \{0,1\}^{(8(k-d))}$.

Compute and store constraints:

m -bit digest, r -bit linear syndrome, optional t -bit chain check to P_{i+1} .

Store a Merkle root over per-chunk digests and a global SHA-256 of the original.

Decoding.

For each chunk i , search for $\text{tail}_i \in \{0,1\}^{(8d)}$ such that the oracle O_i (Section 6) returns true. Compose the recovered chunk $C_i = P_i \parallel \text{tail}_i$. Verify the global SHA-256. If all chunks succeed and the final hash matches, output is guaranteed equal to the original.

Design principles:

- **Locality.** Oracles are chunk-local to enable parallel search.
- **Composability.** Chain checks and a Merkle hierarchy prune cross-chunk combinations early.
- **Determinism.** No probabilistic reconstruction: constraints define a single valid original with overwhelming probability.

4. Format Specification

4.1. Header

- **magic** (4 B): "QRED"
- **version** (1 B)
- **params** (7 B total): k (uint16), d (uint8), m (uint8), r (uint8), t (uint8), flags (uint8)
- **orig_size** (8 B)
- **global_sha256** (32 B)
- **seed_snapshot_len** (1 B), **seed_snapshot** (≤ 64 B): compact snapshot and/or passphrase tag
- Optional **hmac** (32 B) if passphrase binding is enabled

Flags. bit0: passphrase used; bit1: chain enabled; bit2: syndrome enabled; bit3: merkle enabled.

4.2. Chunk record i

- **prefix_i**: $(k - d)$ bytes
- **digest_i**: $\lceil m/8 \rceil$ bytes
- **syndrome_i**: $\lceil r/8 \rceil$ bytes (optional)
- **chain_i**: $\lceil t/8 \rceil$ bytes (optional)

4.3. Trailer

- **merkle_root** (if enabled)
- Optional auxiliary indices

5. Constraint Primitives

Truncated digest m

- **Role:** probabilistic preimage check
- **Expected matches (per chunk):** $E_m = 2^{(8d - m)}$
- **Cost:** $\lceil m/8 \rceil$ bytes

Linear syndrome r

- **Role:** algebraic pruning via $s_i = H_{lin} \cdot v_i$, $H_{lin} \in \{0,1\}^{(r \times 8k)}$
- Reduces the candidate set by a factor of 2^r in expectation
(keeps approximately $1/2^r$)
- Cheap to compute, easy to compose with digest
- **Cost:** $\lceil r/8 \rceil$ bytes

Chain check t

- **Role:** link neighbors to prevent cross-chunk combinatorics
- Example: $\text{trunc}_t(H(P_i \parallel P_{i+1}))$
- **Cost:** $\lceil t/8 \rceil$ bytes

Merkle hierarchy

- **Role:** hierarchical pruning and global integrity
- **Overhead:** compact (root only) if per-chunk digests are stored anyway

Per-chunk net saving (bytes):

$$\Delta_{\text{chunk}} \approx d - (m + r + t)/8$$

Whole file net:

$$\Delta_{\text{total}} \approx C \cdot \Delta_{\text{chunk}} - \text{header/trailer overhead}$$

Amortize per-chunk control bits by increasing k for the same fractional erasure e.

6. Decoding as an Oracle Problem

For chunk i , define the oracle O_i that tests a candidate tail:

Input: P_i (stored), candidate $X \in \{0,1\}^{(8d)}$, neighbor P_{i+1} if chain is enabled, seed.

Construct: $C_i = P_i \parallel X$

Return true iff:

1. $\text{trunc_m}(H(\text{seed} \parallel C_i)) = \text{digest}_i$
2. If enabled, $H_{\text{lin}} \cdot C_i = s_i$
3. If enabled, $\text{trunc_t}(H(P_i \parallel P_{i+1})) = \text{chain}_i$
4. (Optional during search) partial Merkle consistency holds

Uniqueness condition

With independent constraints, the expected number of matches is

$$E[\text{matches}] \approx 2^{(8d - m - r_{\text{eff}} - t_{\text{eff}})} \leq 1$$

where r_{eff} and t_{eff} reflect the effective bits of pruning contributed by the syndrome and chain checks (bounded above by r and t). Choose parameters so $E \leq 1$ per chunk.

7. Complexity: Classical vs Quantum

Let $m_{\text{eff}} = m + r_{\text{eff}} + t_{\text{eff}}$.

Classical (random-oracle model): expected oracle calls to find a preimage that passes all checks scale as

$$T_{\text{classical}} = \Theta(2^{m_{\text{eff}}})$$

Even if $E \approx 1$, finding the solution typically costs exponential time in m_{eff} .

Quantum (Grover / amplitude amplification):

$$T_{\text{quantum}} = \Theta(2^{m_{\text{eff}}/2})$$

given a coherent oracle U_O implementing the joint predicate. This is the core speedup that makes large d feasible.

Implication

To erase a fraction $e = d/k$ and keep uniqueness with negligible false positives, pick $m_{\text{eff}} \approx 8d$. Then

- $T_{\text{classical}} \approx 2^{8d}$
- $T_{\text{quantum}} \approx 2^{4d}$

For $d = 12$ bytes, $T_{\text{classical}} \sim 2^{96}$ (impossible), while $T_{\text{quantum}} \sim 2^{48}$ oracle calls (still enormous, but a roadmap target for future QC at scale). In practice, choose d to match the oracle budget.

8. Projected Storage Reduction

Let $e = d/k$. Per chunk:

$$\text{size_stored} = (k - d) + (m + r + t)/8$$

Fractional size:

$$\rho = \text{size_stored}/k = 1 - e + (m + r + t)/(8k)$$

For fixed (m, r, t) and growing k , overhead amortizes. Under quantum decoding, we select large d (large e) and modest (m, r, t) that still enforce uniqueness, yielding:

$$\rho \approx 1 - e \Rightarrow \text{reduction} \approx e$$

Example (headline)

Choose $e = 0.90$ (erase 90% of each chunk), $k = 1 \text{ MiB}$, $(m, r, t) = (64, 16, 16)$ bits.

Overhead $(m + r + t)/8 = 12 \text{ B}$ per chunk $\Rightarrow \rho \approx 0.10 + 12/2^{20} \approx 0.10001$.

The encoded file is ~10% of the original, i.e., ~90% reduction,
contingent on a quantum decoder capable of handling $m_{\text{eff}} \approx 96$ bits of oracle strength
per chunk (and thus $T_{\text{quantum}} \sim 2^{48}$ coherent oracle evaluations).

Classically infeasible by design.

Today's regime. With small d chosen so classical brute force terminates, ρ is near 1 once (m, r, t) are counted; practical reductions beyond top compressors are not expected on average data.

9. Parameter Guidance

- **Chunk size k.** Larger k better amortizes overhead; increases working-set and I/O.
Typical quantum-target: $k \in [256 \text{ KiB}, 4 \text{ MiB}]$.
- **Erasure d.** Drives savings. Classical tests: $d \in \{2, 3, 4\}$ bytes.
Quantum-target: d into tens or hundreds of bytes (or more),
bounded by search budget.
- **Digest m.** Dominant determinant of search cost.
For uniqueness, start from $m \approx 8d - \delta$ and add syndrome/chain to close the gap.
- **Syndrome r.** Cheap pruning. Sparse random or LDPC-like H_lin works well;
typical $r \in \{8, 16, 32\}$.
- **Chain t.** Helps kill cross-chunk ambiguity; $t \in \{0, 8, 16\}$ suffices.
- **Seeds.** Prefer a stored snapshot (24-64 B). Optional passphrase can be added;
neither is used for secrecy unless HMAC is enabled.

Rule of thumb. Positive net saving per chunk requires $d > (m + r + t)/8$ or amortization
of control bits across larger k.

10. Security, Robustness, and Portability

- **Integrity.** Global SHA-256 and Merkle ensure deterministic acceptance or failure; no silent corruption.
- **Tamper binding (optional).** HMAC over header with passphrase.
- **Portability.** Include a compact seed snapshot; do not rely on live file system metadata.
- **Adversarial inputs.** Parameterize m_{eff} to keep $E \leq 1$ with wide safety margins; randomize H_{lin} per file if desired.

11. Pseudocode (Reference)

11.1 Encoder

```

function QRED_Encode(bytes data, uint16 k, uint8 d, uint8 m, uint8 r, uint8 t, Seed seed):
    N = len(data)
    C = ceil(N / k)
    header = build_header(k,d,m,r,t,N, sha256(data), seed.snapshot)
    out.write(header)

    digests = []
    prefixes = []
    syndromes = []
    chains = []

    for i in 0..C-1:
        chunk = data[i*k : min((i+1)*k, N)]
        if len(chunk) < d: error("chunk shorter than d")
        prefix = chunk[0 : len(chunk)-d]
        full = chunk

        dig_i = trunc_m(sha256(seed || full), m )
        syn_i = trunc_r( linear_syndrome(H_lin, full), r )
        prefixes.append(prefix); digests.append(dig_i); syndromes.append(syn_i)

    for i in 0..C-1:
        next_prefix = (i+1<C) ? prefixes[i+1] : EMPTY
        chain_i = (t>0) ? trunc_t(sha256(prefixes[i] || next_prefix), t ) : EMPTY
        chains.append(chain_i)

    for i in 0..C-1:
        out.write(prefixes[i])
        out.write(digests[i])
        if r>0: out.write(syndromes[i])
        if t>0: out.write(chains[i])

    if merkle_enabled:
        root = merkle_root(digests)
        out.write(root)

```

11.2 Oracle and Decoder (classical brute, per chunk)

```

function Oracle_Test(prefix, candidate_tail, digest, syndrome, chain, next_prefix, seed, m,r,t):
    full = prefix || candidate_tail
    if trunc_m(sha256(seed || full), m) != digest: return FALSE
    if r>0 and trunc_r(linear_syndrome(H_lin, full), r) != syndrome: return FALSE
    if t>0:
        if trunc_t(sha256(prefix || next_prefix), t) != chain: return FALSE
    return TRUE

function QRED_Decode(stream in):
    header = parse_header(in)
    k,d,m,r,t = header.params
    out = empty_buffer()
    chunks = []
    for i in 0..C-1:
        prefix = in.read(k-d for full chunks; last chunk sized)
        digest = in.read(ceil(m/8))
        syndrome = (r>0) ? in.read(ceil(r/8)) : EMPTY
        chain = (t>0) ? in.read(ceil(t/8)) : EMPTY
        next_prefix = peek_next_prefix(in) // or deferred check
        found = FALSE
        for x in 0 .. 2^(8*d)-1:
            tail = int_to_bytes(x, d)
            if Oracle_Test(prefix, tail, digest, syndrome, chain, next_prefix, header.seed, m,r,t):
                chunks.append(prefix || tail)
                found = TRUE
                break
        if not found: error("no candidate for chunk " + i)
    data = concat(chunks)
    if sha256(data) != header.global_sha256: error("global hash mismatch")
    return data

```

12. Implementation Appendix (PHP Skeleton)

Purpose: reference only; not optimized; no quantum paths; suitable for small-d classical validation.

```
<?php

function sha256bin(string $b): string { return hash('sha256', $b, true); }

function trunc_bits(string $bin, int $bits): string {
    $bytes = intdiv($bits + 7, 8);
    $t = substr($bin, 0, $bytes);
    $excess = $bytes * 8 - $bits;
    if ($excess > 0) {
        $last = ord($t[$bytes - 1]) >> $excess;
        $t[$bytes - 1] = chr($last);
    }
    return $t;
}

function lin_syndrome(string $chunk, int $rBits): string {
    // demo: XOR-of-bytes folded into 32-bit, then truncate
    $x = 0;
    $n = strlen($chunk);
    for ($i = 0; $i < $n; $i++) $x ^= ord($chunk[$i]);
    $raw = pack('N', $x);
    $len = intdiv($rBits + 7, 8);
    return substr($raw, 0, $len);
}

function qred_encode(string $inPath, string $outPath, int $k=4096, int $d=3,
                     int $m=24, int $r=8, int $t=8, string $seed=""): void {
    $data = file_get_contents($inPath);
    $N = strlen($data);
    $fh = fopen($outPath, 'wb');
    fwrite($fh, "QRED"); fwrite($fh, chr(1));
    // params
    fwrite($fh, pack('n', $k)); fwrite($fh, chr($d)); fwrite($fh, chr($m));
    fwrite($fh, chr($r)); fwrite($fh, chr($t)); fwrite($fh, chr(0));
    fwrite($fh, pack('J', $N)); fwrite($fh, sha256bin($data));
```

```

$snap = ""; fwrite($fh, chr(strlen($snap))); // seed snapshot len
if ($snap !== "") fwrite($fh, $snap);

$mBytes = intdiv($m + 7, 8); $rBytes = intdiv($r + 7, 8);
$tBytes = intdiv($t + 7, 8);
$prefixes = $digests = $syndromes = $chains = [];
$C = intdiv($N + $k - 1, $k);

for ($i=0,$off=0; $i<$C; $i++,$off+=$k) {
    $chunk = substr($data, $off, min($k, $N - $off));
    if (strlen($chunk) <= $d) throw new RuntimeException("chunk shorter than d");
    $prefix = substr($chunk, 0, strlen($chunk) - $d);
    $digest = trunc_bits(sha256bin($seed . $chunk), $m);
    $syn = ($r>0) ? trunc_bits(lin_syndrome($chunk, $r), $r) : "";
    $prefixes[] = $prefix; $digests[] = $digest; $syndromes[] = $syn;
}
for ($i=0; $i<$C; $i++) {
    $next_prefix = ($i+1<$C) ? $prefixes[$i+1] : "";
    $chain = ($t>0) ? trunc_bits(sha256bin($prefixes[$i] . $next_prefix), $t) : "";
    $chains[] = $chain;
}
for ($i=0; $i<$C; $i++) {
    fwrite($fh, $prefixes[$i]);
    fwrite($fh, $digests[$i]);
    if ($r>0) fwrite($fh, $syndromes[$i]);
    if ($t>0) fwrite($fh, $chains[$i]);
}
fclose($fh);
}

function qred_decode(string $inPath, string $outPath): void {
    $f = fopen($inPath, 'rb');
    if (fread($f,4)!=="QRED") throw new RuntimeException("bad magic");
    $ver = ord(fread($f,1));
    $k = unpack('n', fread($f,2))[1]; $d=ord(fread($f,1)); $m=ord(fread($f,1));
    $r=ord(fread($f,1)); $t=ord(fread($f,1)); $flags=ord(fread($f,1));
    $N = unpack('J', fread($f,8))[1]; $sha = fread($f,32);
    $snapLen = ord(fread($f,1)); $seed = ($snapLen>0) ? fread($f,$snapLen) : "";
    $mBytes = intdiv($m+7,8); $rBytes = intdiv($r+7,8); $tBytes = intdiv($t+7,8);

```

```

$C = intdiv($N + $k - 1, $k);
$out = "";
for ($i=0; $i<$C; $i++) {
    $lastSize = ($i<$C-1) ? $k : ($N - $k*($C-1));
    $prefixLen = $lastSize - $d;
    $prefix = fread($f, $prefixLen);
    $digest = fread($f, $mBytes);
    $syn = ($r>0)? fread($f, $rBytes):"";
    $chain = ($t>0)? fread($f, $tBytes):"";
    // Peek next prefix for chain check
    $pos = ftell($f);
    $next_prefix = "";
    if ($i<$C-1) {
        $nextSize = ($i+1<$C-1) ? $k : ($N - $k*($C-1));
        $next_prefix = fread($f, $nextSize - $d);
    }
    fseek($f, $pos);
    $found = null;
    $space = 1 << (8*$d);
    for ($x=0; $x<$space; $x++) {
        $tail = "";
        for ($b=$d-1; $b>=0; $b--) $tail = chr(($x >> (8*$b)) & 0xFF) . $tail;
        $full = $prefix . $tail;
        if (trunc_bits(sha256bin($seed.$full), $m) !== $digest) continue;
        if ($r>0 && trunc_bits(lin_syndrome($full,$r), $r) !== $syn) continue;
        if ($t>0) {
            if (trunc_bits(sha256bin($prefix.$next_prefix), $t) !== $chain) continue;
        }
        $found = $full; break;
    }
    if ($found==null) throw new RuntimeException("no candidate in chunk $i");
    $out .= $found;
}
fclose($f);
if (sha256bin($out) !== $sha) throw new RuntimeException("global hash mismatch");
file_put_contents($outPath, $out);
}

```

Notes. This skeleton keeps the critical ideas compact. Real implementations should stream I/O, validate bounds, and add Merkle verification and error handling.

13. Evaluation Plan

Datasets. Text/JSON/logs (structured), uncompressed binaries, already-compressed (control), random (control).

Baselines. zstd-19, brotli-11, paq/paq8.

Parameters. $k \in \{1 \text{ KiB}, 4 \text{ KiB}, 64 \text{ KiB}\}$, $d \in \{2, 3, 4, 6\}$, $m \approx 8d$, $r \in \{8, 16\}$, $t \in \{0, 8\}$.

Metrics. Encoded size ratio ρ ; classical decode attempts per chunk; wall-clock decode time; false-match rate; pass/fail on hash.

Success criteria (classical lab). Deterministic correctness on small d ; empirical match to predicted costs; no silent failures.

Quantum roadmap validation. Map the oracle to a reversible circuit; estimate gate counts for SHA-256 truncation and linear checks; extrapolate feasible (d, m_{eff}) with assumed quantum resources.

14. Quantum Implementation Roadmap

Oracle unitary U_O . Build a coherent predicate for (digest, syndrome, chain).

- SHA-256 reversible circuits are known in literature; use truncation by discarding high bits.
- Linear syndromes are Clifford-friendly.

Amplitude amplification. Standard Grover iterations; per-chunk search in superposition space $|x\rangle$, $x \in \{0,1\}^{(8d)}$.

Data access. Seed and stored constants are classical; embed as control parameters.

Prefix and neighbor prefixes are classical inputs loaded to quantum ancillas.

Parallelization. Run per-chunk searches in parallel across quantum processors; or pipeline chunks.

Resource estimation. For target d and m_{eff} , estimate $2^{(m_{eff}/2)}$ oracle calls; compute depth \times calls; incorporate error-correction overheads.

Hybrid pruning. Classical prefilters (e.g., linear checks) can be pushed ahead to lower oracle load.

15. Limitations and Risks

- **Impossibility bounds.** This is not a universal better-than-entropy compressor; it trades compute for storage and relies on constraints, not magic.
- **Classical practicality.** Aggressive settings are intentionally infeasible today.
- **Quantum uncertainty.** Timelines and practical oracle costs are uncertain; resource estimates must be revisited.
- **Portability.** If seed snapshots or passphrases are lost, decoding fails by design.
- **Adversarial inputs.** Choose conservative m_{eff} and randomized matrices to bound worst-case collisions.

16. Conclusion

Q-Reduct reframes lossless storage as compute-for-storage exchange with an explicit quantum decoding advantage. By erasing a large fraction of payload and storing compact constraints, we shift complexity to a search oracle. Classically, only small d is testable; under quantum decoding, projected reductions track the erasure fraction, enabling on the order of 80-90% size reduction for high e with sufficient quantum resources and properly tuned constraints. The specification, pseudocode, PHP skeleton, and evaluation plan provided here support immediate laboratory validation and future quantum mapping.

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Appendix A — Symbols at a Glance

Symbol	Definition
N	Original size (bytes)
k	Chunk size (bytes)
d	Bytes erased per chunk
e	Erasure fraction = d/k
m, r, t	Digest, syndrome, chain bits
C	Chunk count = $\lceil N/k \rceil$
Δ_{chunk}	Net saving per chunk = $d - (m+r+t)/8$
E	Expected matches $\approx 2^{(8d - m - r_{\text{eff}} - t_{\text{eff}})}$
m_{eff}	Effective constraint strength = $m + r_{\text{eff}} + t_{\text{eff}}$
T_classical	Classical complexity = $\Theta(2^{(m_{\text{eff}})})$
T_quantum	Quantum complexity = $\Theta(2^{(m_{\text{eff}}/2)})$
ρ	Fractional size = $\text{size_stored}/k$

Appendix B — Parameter Tables (examples)

Per-chunk net saving (bytes): $\Delta_{\text{chunk}} = d - (m+r+t)/8$

Note on notation: In mathematical formulas we use \parallel for concatenation; in pseudocode and implementation we use `||`.

Classical-testable parameters (small d)

k (Bytes)	k (KiB)	d (Bytes)	e = d/k	m	r	t	Δ_{chunk} (B)	ρ	Reduction
4,096	4	3	0.000732	24	8	8	-2	≈ 1.00049	-0.049%
65,536	64	6	0.000092	48	16	16	-4	≈ 1.00006	-0.006%

Quantum-target regime (90% headline example)

k (Bytes)	k (KiB)	d (Bytes)	e = d/k	m	r	t	Δ_{chunk} (B)	ρ	Reduction
1,048,576	1	943,718	0.90	64	16	16	943,706	≈ 0.10001	$\approx 90.0\%$

In the quantum regime: $e \approx 0.9$, overhead $(m+r+t)/8 \ll k$, enabling dramatic reduction with quantum oracle budget.

Appendix C — Pseudocode: Merkle and Syndrome Construction

```
function merkle_root(list digests):
    level = digests
    while len(level) > 1:
        next = []
        for j in 0..step2(len(level)):
            a = level[j]
            b = (j+1<len(level)) ? level[j+1] : level[j]
            next.append( sha256(a || b) )
        level = next
    return level[0]

function random_sparse_Hlin(r, bitsPerChunk, density):
    // return r x bitsPerChunk binary matrix with given sparsity
```

Appendix D — Implementation Checklist

- Streaming encoder/decoder; bounds checks; endian consistency
- Stable seed snapshot; optional passphrase; deterministic seed derivation
- Robust header validation; versioning
- Optional Merkle root; chunk digests already present
- Unit tests: oracle truth table; collision statistics; chunk independence
- Benchmarks: per-chunk oracle cost; end-to-end decode time; corpus ratios
- Security: HMAC option; tamper detection; controlled failure semantics