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Theoretical Model for Balancing Reliability and Latency in Hybrid CRC–Polar Coding for 6G Wireless Networks

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Abstract—**Polar codes and their CRC-assisted derivatives have become important facilitators of ultra-reliable low-latency communication (URLLC) in 5G wireless networks, especially in the cases of applications where short packets have to be transmitted, and error rates must be nearly zero, such as autonomous vehicles, remote medical treatments, and automation of industrial devices. Although the dependability has been proved to be beneficial when the incorporation of codes of CRC-Polar is performed previously, the studies frequently analyze the qualities of the reliability and latency separately without taking into account the trade-offs inherent to 6G URLLC. This paper fills this gap by coming up with a single analytical model that explicitly characterizes the dependence of blocklength, their CRC length, and successive cancellation list size (size of successive cancellation) on the block error rate and the decoding latency. The it is a methodology that incorporates the finite-blocklength information theory, channel polarization principles and the analysis of instruments of CRC errors detection and is confirmed and validated over extensive simulation over realistic 6G parameters. The findings reveal that list decoding with the aid of CRC yields a significant reliability improvement in short packet cases, and the increases in decodinglatency with larger lists are nearly linear, although there is a large gain in reliability with a considerable like impact of CRC length. The paper defines limited optimum areas of the parameters under which URLLC requirements are met, the significance of co-designing of parameters. In general, the framework suggested will give viable considerations towards realizing hybrid codes of CRC-Polar mechanisms to reach ultra-high reliability without breaking the sub-milliseconds delay limitations in future 6G networks.**

Keywords-Polarcodes; Blocklength; Latency

I. INTRODUCTION

The idea of sixth-generation (6G) wireless networks is highly influenced by the pursuit of highest level of performance particularly in the field of ultra-reliable low-latency communication (URLLC), intelligent sensing, and the field of real-time control. Contrary to previous generations, which primarily paid attention to a higher data rate, 6G will be able to serve the needs of applications that require a near-instantaneous connection and near-error-free transmission, such as remote surgery, smart manufacturing, autonomous driving, tactile internet, and distributed robotics. These new applications demand reliability of the order of 10-7 and end-to-end latency of less than one millisecond, which puts tremendous stress on current error-control coding schemes [1].

The polar codes are one significant achievement and breakthrough in channel coding as they are the first family of codes that are demonstrated to be approaching the capacity limits needed by the next generation wireless systems. They have remained relevant with the development to 6G on where efficient and reliable

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coding schemes are crucial towards sustaining the URLLC services [2]. Nevertheless, Polar codes are efficient at moderate block length but at the very short block lengths needed by URLLC, the efficiency is sub-optimal. To overcome this drawback, Cyclic Redundancy Check (CRC) bits are now added to the decoding process led to CRC-aided Polar (CA-Polar) codes. CRC help makes decoding choices more effective and performance in terms of block error rate measurably better with severe latency demands [3].

The combination of CRC and Polar codes, however, provides some new challenges. Even though CRC bits boost reliability that reduces the probability of the decoding error, it leads to the increased probability of effective code length and decreased decoding complexity, which contains a straightforward effect on the latency. When both reliability and latency are equally important, in 6G environment such interaction turns out to be a balance act. Increasing one of the performance measures will likely cost the other, and the existing research does not yet provide a coherent analysis framework on how to relate and optimise this reliability-latency trade-off in future wireless systems [2].

The majority of the current studies in CA-Polar codes focused on decoding strategies, improvement of list-size, and performance gains in URLLC conditions [3]. Although these contributions are important in terms of implementation as well as system-design, they do not tend to include a detailed analytical framework that would jointly address the information-theoretic limits, decoding delay, and latency-reliability requirements that might be imagined in 6G networks. System designers continue to be confronted with the difficult problems on how to set the best lengths of multiple CRCs, the best sizes of blocks, and the best settings of the decoders to both meet the goals of maximum reliability as well as the goals of maximum latency.

The gap noted in this paper was filled by coming up with an analytical model to describe the formal correlation between reliability and latency in hybrid CRC-Polar codes systems. The model combines the concepts of information theory and error-control coding to offer an organized method of examining how parameters of the system block length, CRC length, list size and signal-to-noise ratio combine to determine decoding delay and block-error rate. In this way, the study offers an analytical basis that can be used to optimize future link-level and system-level designs at the 6G in URLLC.

II. LITERATURE REVIEW

The consideration of reliability and latency issues of hybrid CRC and Polar coding should be based on the preservation of communication theory and the new developments aimed at 6G short-packets transmission. Since the 6G systems are designed to provide their capabilities in terms of ultra-reliable low-latency communication, traditional coding strategies have limited performance requirements [1]. Polar codes, although useful to a contemporary wireless system, have drawbacks concerning small block length, which inspires the use of CRC-aided decoding techniques to support reliability [3]. The recent works have also emphasized the necessity of simultaneous choice between composite complexity and latency regarding implementing CRC with Polar codes in the next-generation networks [3]. Nevertheless, the literature is mainly concerned with performance improvement, as opposed to coherent analytical modelling. This work discusses major concepts and literature that drive a systematic framework in the study of the reliability-latency trade-offs in hybrid CRC-Polar coding to the 6G systems in future.

A. Background on Error-Control Coding for 6G

The process of switching between the fifth-generation (5G) and the sixth-generation (6G) wireless networks is a radical change in the priorities of communication systems. Instead of main data rates, 6G is more focused on ultra-high reliability, very low latencies, massive connectivity, and smart network behavior. Remote surgery, autonomous transportation, industrial automation and real time control systems are some of the applications that are projected to rely on ultra-reliable low-latency communication (URLLC). True to its name, these applications demand very low-latency (less than a single millisecond) over a distance, and coverability of up to or above 99.99999%.

The traditional channel coding methods, including turbo code, convolutional code and low-density parity-check (LDPC) code, are highly efficient in long block coding but become extremely ineffective in short-packet transmissions. URLLC services are characterized by the use of packet sizes of a few tens to hundreds of bits and finite blocklength effects are dominant, with no longer being able to apply the classical assumptions in the asymptotic analysis. Consequently, both the attainment of high reliability and low latency start to get even more complex under those circumstances, which is why the investigation of new coding approaches focused on short packets and the need to support very high connectivity rate becomes necessary [4].

The Polar codes have proved to be a viable implementation into the current wireless system through a structured approach to building coupled with appropriateness to short block lengths. They are practically relevant and adaptable when used as offered in 5G New Radio control channels. Nevertheless, Polar codes coded with simple successive cancellation algorithms in spite of their theorical advantages have performances losses at small block lengths, and this disadvantage restricts their performance in the URLLC environment. To eliminate this drawback, more sophisticated decoding algorithms, including successive cancelation list decoding and CRC aided decoding have been introduced to enhance error-correction capability without incurring too much increase in the complexity of the code [4].

Introduction of Polar codes coupled with the addition of cyclic redundancy check (CRC) bits has been very successful in improving decoding accuracy. CRC-aided Polar (CA-Polar) codes utilize CRC bits, to direct the decoder toward the most probable list of codewords among a list of implicit meaning aided by the CRC bits, which results in lower block error rates and errors go undetected. This procedure proved to be highly effective in enhancing reliability when used in the URLLC setting, and in particular, when used together with the effective list-decoding schemes which are aimed at the transmission of short packets [5].

This is however subject to important trade-offs due to the addition of CRC bits. Even though CRC ensures more accurate decoding, it also raises the effective code length and complexity of decoding turning out to be detrimental to processing delay. Even minor increments on decoding time in latency not insensitive 6G-applications can break strict latency budgets. Thus, the length of CRC and decoding algorithm, as well as the list size, should be optimized so that the reliability benefits could not be at the cost of the intolerable latency penalties [6].

Recent reports have also indicated a further point that CRC selection is not simply a mechanism to detect errors but an important determinant that determines the overall outcome of CA-Polar codes. Configurations of CRC may have massive impact on the behavior of decoding, error floors and residual error probabilities especially in short block length regimes. Such effects are becoming more and more apparent as the systems become 6G, at which extreme reliability and ultra-low latency need to be met simultaneously [5].

Though the number of research on Polar codes and sided effects of CRC-aided decoding is continuously increasing, the vast majority of what is currently researched involves variations in performance or efficiency in the implementation by their own. It still does not have cohesive analytical paradigms that simultaneously model reliability, decoding complexity and latency over finite blocklength conditions. With 6G networks at the edges of wireless performance, it is necessary to know how parameters of code construction and decoder configurations work together. The gap is important in building coding schemes that are capable of satisfying the demanding and interconnected requirements of reliability-latency that will be needed in future wireless systems and is what constitutes the motivation behind the analytical strategy taken in this research.

B. Latency–Reliability Trade-off in Ultra-Reliable Low-Latency Communication (URLLC)

It has become a known technical challenge in the development of 5G-6G wireless network evolution to fulfill the joint requirement of ultra-low latency and ultra-high reliability. Reliability in the URLLC often takes into account the chance of a successful block decoding and the latency defines encoding, transmission, decoding, and processing delays. The 6G systems of the future are projected to reach unprecedented levels of extreme stays and high reliability of 99.99999%. The current channel coding schemes perform poorly on such constraints since any attempt to enhance reliability by adding more redundancy or adding effort to the decoding process will probably increase the latency. The recent surveys and analytical research focus on the fact that this tension is especially acute in short-packet transmission, in which packets can include less than several hundred bits, and the assumptions of asymptotic coding cannot be applied [5] [6]. Accordingly, the issue of reliability-latency trade-off has taken the front seat in the literature addressing beyond-5G and 6G channel coding.

Polar codes have gained a lot of interest in this respect because of its block-and-orderly construction and long block-length suitability. They are actually used in the 5G control channels and prove to be practically useful, but various experimental works indicate that standard successive cancellation decoding performance is suboptimal in URLLC regimes. To solve this, CRC-aided Polar coding has become one of the crucial improvements where CRC bits are used to guide list-based decoders to choose a correct codeword among the possible ones. Xiang demonstrated that list and stack decoding with the help of CRC can be used to achieve high block error rate when using URLLC when working with New Radio systems. Equally, Sy showed that the combination of CRC and Polar codes not just improves the accuracy level, but it also expands the error correction as well as the detection level, especially when there are short packets. These advantages come at a cost, however, since the complexity of the decoding process and processing delay also increase as the size of the list and the length of the CRC increase. Channel coding reviews of B5G and 6G always note that the reliability of CRC-aided Polar codes is better than standalone Polar codes, but the latency performance of the scheme is highly sensitive to parameters configuration, which include the length of CRC, the size of the list, and the decoding architecture [4].

In addition to decoder design, the reliability-latency trade-off has been recently modded in the context of a system problem, no longer a problem of coding. According to Zhang and Tong, due to extreme connectivity in the 6G, connectedness cannot be achieved without jointly optimised coding schemes with latency or deadlines, finite blocklength consequences, and hardware constraints. Although the grade of programs supported by CRC-aided Polar codes represents an exciting tradeoff between reliability and complexity, the current literature is inclined towards empirical tests of performance, or algorithm enhancements in absolute solitude. The absence of cohesive analytical models by which the reliability gains of CRC integration are converted to the latency penalty given realistic short-packet and latency constraints have not been yet established [6]. Gautam et al. further indicate that much of the open research problems in 6G coding are concerned with the insight into such trade-offs at a theoretical level, especially with respect to safety-critical and time-critical applications. Consequently, the literature also indicates that there is a gap in analytical characterisation of combined effects of CRC length, decoding complexity as well as blocklength and latency and reliability that requires further research on hybrid CRC-Polar coding schemes that could be applicable in 6G URLLC conditions [2].

C. Theoretical Foundations Relevant to Hybrid CRC–Polar Coding

Theoretical basis on which hybrid CRC- Polar coding with 6G URLLC system relies. The theories give the strict scientific basis of the analytical models that will be built in future. To the Nigerian researcher and engineers, knowledge in these principles may assist them in developing dependable low-latency communication systems that can be used in autonomous vehicles, smart grids, remote medical treatment, and automation in factories among others. Finite blocklength information theory, polarization of channels, CRC detection of errors, and the latency reliability tradeoff are the fundamental theories.

Information-Theoretic Capacity and Coding Limits. The Shannon channel capacity theory gives the rate of transmission of a noisy channel that is always reliable. In the case of an AWGN channel the capacity (C) is written as:

$$C = log2(1 + SNR)\ bits/channeluse \quad (1)$$

(Ahmadipour et al., 2022)

Such short packets are however needed in URLLC in 6G and classical Shannon capacity fails. The short operation of packets is explained by the finite blocklength approximation:

$$R \approx C - \sqrt{\frac{V}{n}}, Q^{-1}(\varepsilon) \quad (2)$$

Where:

1) (C) is the Shannon capacity
2) (V) is channel dispersion
3) (n) is the blocklength
4) (ε) is the target error probability$Q$ −
5) $((Q^{-1}(\cdot))$ is the inverse Gaussian function

This expression suggests that the lower (n), the higher the penalty term is, which means that the feasible rate will narrow. This was the reason why Polar codes with CRC are best at URLLC scenarios and cover the losses of reliability still covering short blocklengths.

Polarization Theory and Structure of Polar Codes. Polarization is applied to specific parts of the channel, which are constructed into polar codes [5]. The synthetic channels are polarized to highly reliable channels and highly unreliable channels by recursively concatenating $(N = 2^k)$ identical binary-input memoryless channels. Recursive development of the reliability can be defined using Bhattacharyya parameter (Z(W)):

$$Z(W+) = Z(W)2Z(W-) = 2Z(W) - Z(W)2Z(W-) = 2Z(W) - Z(W)2 \quad (3)$$

Unreliable channels are frozen whereas reliable channels carry information bits. When the blocklength is short like in URLLC, CRC-aided list decoding is used to pick the proper decoding path out of candidate codewords and is therefore shown to improve performance [7].

Error Detection Theory and CRC Undetected Error Probability. CRC codes provide polynomial-based error detection. For L_{CRC} -bit CRC, the probability of an undetected error is bounded by:

$$[P_{\mathrm{undetected}} = 2^{-L_{\mathrm{CRC}}}] \quad (4)$$

CRC helps in the Polar list decoding to authenticate the candidate codewords so that the appropriate path is adopted. CRC enhances reliability in URLLC where a single error (not found) may lead to enormous effects yet without introducing much decoding latency (Sauter et al., 2023).

Finite Blocklength Latency–Reliability Trade-Off. In URLLC, reliability P_e and latency Tare are poor goals. The finite block length theory gives an error probability estimate:

$$\left[P_e \approx Q\left(\frac{\sqrt{n}(C - R)}{\sqrt{V}}\right)\right] \quad (5)$$

Where (V) is the dispersion of the channel. It demonstrates by this equation that a shorter blocklength to support latency requirements has more probability of error unless the code is optimized to offset that error probability. Hybrid CRC-Polar codes give a trade-off, with high reliability at small blocklengths at a low cost in terms of latency, which suits the 6G URLLC specifications [8].

D. Fundamentals of Polar Codes

Linear block codes Arikan introduced polar codes that allow the capacity of symmetric binary-input memoryless channels to be obtained when used with successive cancellation decoding in the limit as the block length is increased. They have a specialty known as polarization of the channels that turn the same physical channel or channels into virtual channels, either very reliable or nearly totally noisy. This characteristic is especially desirable when Ultra-Reliable Low-Latency Communication (URLLC) is considered in 6G systems being particularly the case because blocklengths are concise, and maintenance levels may be very low which dictates highly efficient code layouts [8].

Channel Polarization Mechanism. Channel polarization involves recursively combining $(N = 2^n)$ copies of a binary-input channel (W) using a linear transformation defined by the generator matrix:

$$\left[G_N = F^{\otimes n}\right] \tag{6}$$

Where $F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ is the basic kernel matrix, and $(\otimes\, n)$represents the n-th Kronecker power.

Through this transformation, the synthetic channels $(W_N^{(i)})$ polarize into two distinct types:

1) Highly reliable channels, with Bhattacharyya parameter $(Z(W_N^{(i)}) \to 0)$
2) Highly unreliable channels, with $(Z(W_N^{(i)}) \to 1)$

The reliability evolution is recursively described as:

$$[Z(W^+) = Z(W)^2] \tag{7}$$

$$[Z(W^-) = 2Z(W) - Z(W)^2] \tag{8}$$

Reliable channels are assigned information bits, while unreliable channels are frozen. In URLLC contexts, where short packet transmission is required, CRC-assisted list decoding helps compensate for the imperfect polarization at short blocklengths, enhancing reliability without increasing latency [9].

Successive Cancellation (SC) Decoding. Successive Cancellation (SC) is the standard decoding algorithm for polar codes. SC decoding sequentially estimates each bit based on the received sequence and previously decoded bits. Let $(\hat{u}_i)$ be the estimate of the i-th bit:

$$\hat{u}_i = \begin{cases} 0, & \text{if } i \text{ is a frozen bit} \\ \arg \max\limits_{u_i \in \{0,1\}} W_N^{(i)}(y_1^N, \hat{u}_1^{i-1} \mid u_i), & \text{otherwise} \end{cases} \tag{9}$$

SC decoding is simple and achieves capacity asymptotically, but performance degrades at short blocklengths typical in URLLC scenarios [10].

List Decoding and CRC-Aided Polar Codes. To improve performance at short blocklengths, list decoding maintains a list of the (L) most likely codewords. The final codeword is selected using a CRC appended to the information bits:

$$\left[\mathbf{u} = \arg \min_{\mathbf{u} \in \mathcal{L}} \mathrm{CRC}(\mathbf{u})\right] \tag{10}$$

Here, (L) denotes the list of candidate codewords. CRC-aided list decoding reduces the error probability significantly, approaching maximum likelihood decoding while keeping complexity manageable. This makes CRC–Polar codes highly suitable for short-packet, low-latency transmissions in 6G URLLC [10].

Relevance to 6G URLLC.To achieve 6G URLLC targets of (10^{-7}) error rates or lower, and end-to-end latencies of (1 ms) or less, the hybrid CRC-polar strategy of error control is appealing since a suitable choice of parameters allows achieving very strong performance of short blocks and having manageable complexity of decoding [11]. The trade-off between reliability and low decoding latency puts the hybrid scheme on a realistic list of mission-critical services in resource-constrained deployment environments like most Nigerian urban and rural areas.

E. Limitations of Existing Hybrid CRC–Polar Implementations

Although CRC-Polar hybrid codes provide substantial improvement, currently, its implementation has multiple limitations that limit its use in ultra-reliable low-latency communication (URLLC) scenarios including the use of 6G networks. It is important to comprehend these limitations to create motivation of the proposed theoretical model and even control the parameter optimization.

Complexity and Latency Trade-Off. The biggest weakness is the complexity of decoding that is brought about by list decoding. As successive cancellation list (SCL) decoding is an error reduction method, it increases proportional to the number of lists (L) and logarithmically with blocklength (N) (Shuval and Tal, 2024):

$$[\mathcal{C}_{\text{SCL}} \approx L \cdot N \log_2 N] \tag{11}$$

Adding CRC verification introduces an additional cost proportional to the number of candidates:

$$[\mathcal{C}\text{Hybrid} \approx L \cdot N \log_2 N + L \cdot k\text{CRC}] \tag{12}$$

Here, (k_{CRC}) denotes the per-candidate CRC check operations. In latency-constrained URLLC systems, excessive (L) values or large blocklengths may violate the end-to-end delay budget, making the scheme impractical in some 6G applications [10] [12].

Finite Blocklength Performance Degradation. Another limitation is the performance drop at extremely short blocklengths ($(N < 128)$ bits). While CRC-aided Polar codes improve reliability compared to conventional Polar codes, the probability that the correct codeword is not included in the candidate list $((P_{\text{missed}}))$ increases for very small (N) , especially under fading channels:

$$\left[P_{\text{missed}} \approx Q\left(\frac{\sqrt{N}(C - R_{\text{eff}})}{\sqrt{V}}\right)\right] \tag{13}$$

Where (C) is channel capacity, (V) is channel dispersion, and (R_{eff}) is the effective code rate including CRC overhead [12]. This finite-blocklength limitation is particularly relevant for 6G URLLC packets, which often require extremely short payloads to meet latency constraints.

CRC Overhead and Rate Loss. Adding CRC parity bits reduces the effective information rate:

$$\left[R_{\text{eff}} = \frac{K}{N} \longrightarrow R_{\text{eff}} = \frac{K + L_{\text{CRC}}}{N}\right] \tag{14}$$

While the trade-off is necessary for error detection, excessive CRC length may limit throughput, which is a critical concern for high-speed 6G services. Designers must carefully balance CRC length to achieve reliability without imposing excessive rate loss [12].

Hardware and Energy Constraints. CRC verification and list decoder High-performance List decoders are very computationally intensive. This translates to power consumption and thermal constraints that could be a significant issue to mobile devices or edge nodes in 6G networks which are usually ignored in the theoretical model. Thus, obtaining realistic real-world implementations might require algorithmic tradeoffs or simplifications e.g. adaptive list size or early-termination SCL decoding [13].

Channel Model Assumptions. The majority of hybrid CRC-Polar analyses make use of either Additive White Gaussian Noise (AWGN) channels or idealized Rayleigh fading. Nevertheless, more complex propagation conditions, such as frequency-selective fading, interference and active mobility, will be faced with 6G networks. Current models might fail to reflect realistic performance in these conditions, which limits the ability to use them to predict at the system level [13].

III. METHODOLOGY

The methodological framework to construct a theoretical model to capture the reliability-latency trade-off of hybrid CRC-Polar coding of 6G URLLC systems. The procedure is designed to consist of three stages, namely mathematical modelling, the incorporation of the reliability and latency into a single analysis, and verification through simulation. The construction of this framework is such that the theoretical input is created with a solid basis on code theory, computational complexity analysis, and empirical testing of performance under realistic 6G conditions.

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A. Mathematical Modelling

The initial step forms the basic expressions of analysis that are needed to measure the reliability and latency attributes of hybrid CRC-Polar codes. This contains: (i) block-length reliable limits in CRC aided decoding; (ii) block length latency models in SCL decoding; and (iii) polynomially weight distribution in CRC detection. These parts are the building blocks of the unified trade-off model that was developed.

Finite-Blocklength Reliability Bound for Hybrid CRC–Polar Codes. CRS-Polar Hybrid codes are designed to work with short blocklengths that URLLC traffic has; therefore, the performance of these codes cannot be measured on the basis of asymptotic Shannon capacity. Finite-blocklength analysis, on the other hand, gives a better value of block error rate (BLER). The probability of blockerror is approximated as normal approximation is given as follows according to blocklength N, rate R, and channel dispersion V:

$$P_e \approx Q\left((C - R) * \mathrm{sqrt}(N/V)\right) \qquad (15)$$

Where

1) C is the channel capacity,
2) Vis the channel dispersion,
3) Q(.) is the Gaussian Q-function,
4) R=K/N represents the effective rate including CRC overhead.

For hybrid CRC–Polar codes, the effective reliability includes both decoding failure and undetected error probability. Therefore, the overall reliability expression is:

$$P\_total = P\_decoder + P\_undetected \quad (16)$$

This formulation aligns with finite-blocklength principles introduced by Polyanskiy, which remain essential for modelling 6G URLLC reliability requirements.

Latency Modelling for Successive Cancellation List Decoding. The latency of SCL decoding is influenced by blocklength, list size L, CRC length, and hardware computational cycles. Under typical implementations, the decoding latency T_dec is expressed as:

$$T\_dec = (N * \log2(N)) * c + (L - 1) * d \quad (17)$$

Where

1) c represents the average computational cost per SC stage,
2) d represents the additional cost per extra list-path extension.

The total latency T_total includes buffering, CRC checking, and queueing delay:

$$\mathbf{T\_total = T\_dec + T\_crc + T\_queue} \quad (18)$$

Since URLLC demands sub-millisecond end-to-end delay, only small L values are feasible unless the system introduces parallel processing. This analytical formulation is consistent with studies by Tal and Vardy (2015) and Bennis et al. (2018), which link list-size growth directly to latency increase in short-packet decoding.

CRC Detection Probability and Weight Distribution Analysis. CRC effectiveness in hybrid CRC–Polar coding depends on its ability to detect erroneous codewords among multiple SCL decoding paths. The probability of undetected error is approximated as:

$$P\_undetected \approx 2\hat{}(-r) * W_m in \qquad (19)$$

Where:

1) r is the CRC length,

2) W_{min} is the minimum Hamming weight among invalid candidate code words.

This expression reflects how CRC polynomial weight distribution determines error detection capability. Prior studies show that carefully selected CRC polynomials improve list decoder discrimination, thereby reducing undetected error probability while minimally impacting latency [13] [14] [15].

B. *Integration of Reliability and Latency into a Unified Analytical Framework*

This stage assembles the mathematical elements in Phase 1 to one theoretical framework, which describes the dependence of reliability and latency between the hybrid coding of CRC and Polar. It is aimed at conceptually capturing reliability and latency as not single performance characteristics, but as joint functions under the control of coding parameters like blocklength, CRC length and list size. This combined analytical model is the keynote of the proposed theoretical input of this study, a systematized approach to determining parameters settings that fulfill 6G URLLC specifications.

Derivation of the Joint Reliability–Latency Expression. The total reliability expression consisted of decoder-induced errors and CRC undetected errors:

$$P\_total = P\_decoder + P\_undetected \quad (20)$$

Given that:

$$P\_decoder \approx Q\left((C - R) * sqrt(N / V)\right), \quad (21)$$

The combined reliability function becomes:

$$P\_undetected \approx 2^{\wedge}(-r) * W\_min,$$

$$P\_total \approx Q\left((C - R) * sqrt(N / V)\right) + 2^{\wedge}(-r) * W\_min \quad (22)$$

Latency, on the other hand, is governed primarily by SCL decoding behaviour:

$$T\_total = (N * log2(N)) * c + (L - 1) * d + T\_crc + T\_queue \quad (23)$$

In order to couple reliability and latency, we state the list size L and the CRC length r, also a determinant of reliability as contributors towards latency overhead. As such, unified trade-off model will be represented as:

$$\begin{aligned} P\_total &= f(N, R, r, L) \\ T\_total &= g(N, r, L) \end{aligned} \quad (24)$$

Where $f(\cdot)$ and $g(\cdot)$ are derived from the earlier expressions. Combining both leads to the central relationship:

$$P\_total = Q\left((C - (K - r) / N) * sqrt(N / V)\right) + 2^{\wedge}(-r) * W\_m \quad (25)$$

$$T\_total = (N * log2(N)) * c + (L - 1) * d + T\_crc + T\_queue \quad (26)$$

This expression indicates that the longer the CRC length r becomes, the more high the reliability but loses rate hence throughput. Likewise, P_decoder is improved when list size L increases but T_total improves almost linearly. The derived expressions are thus the measure of inherent coupling between reliability and latency of hybrid coding in CRC-Polar coding.

Optimal Parameter Identification. To identify optimal coding parameters for 6G URLLC, we define constraints:

$$\begin{aligned} P\_total &\le \varepsilon\_target \\ T\_total &\le \tau\_target \end{aligned} \quad (27)$$

Where:

1) ε_target represents the maximum tolerable block error probability (e.g., 10−5),

2) τ_target represents the maximum latency bound (e.g., 1 ms end-to-end).

The parameter optimization problem is therefore:

minimize P_total

subject to T_total ≤ τ_target

Or alternatively:

minimize (T_total)

subject to P_total ≤ ε_target

This leads to a constrained search over (N,r,L). This analytical optimization framework is essential for determining feasible configurations for 6G systems, especially when short blocklengths impose strict performance limits.

Interpretation for 6G URLLC Design. The coherent analytical model above presents some of the important conclusions of the 6G design:

The CRC length r produces diminishing returns: As r becomes large, fewer undetected errors will be eliminated, but the diminishing returns start to decrease once r has become moderate (16-24 bits), and overhead increases only.

1) *List size L has the strongest influence on latency:* The benefits of scale of L to significant improvements on the latency but the latency cost is linear and can exceed URLLC limits.

2) *Blocklength N dictates the fundamental trade-off boundary:* Longer blocklengths reduce decoding error probability but are incompatible with extremely short-packet URLLC traffic.

3) *Optimal configurations exist only in narrow parameter regions:* This matches the previous results in the literature that hybrid CRC-Polar codes achieve better performance than polar-only codes, but co-design is essential to optimize between performance and delay [11] [13].

C. Hybrid Reliability–Latency Integration Framework

This work constructs the convergent analytical framework according to which the reliability behaviour of the hybrid CRC-Polar coding scheme is connected to the decoding latency characteristics of hybrid coding scheme in the context of finite-blocklength URLLC conditions.

The bounds on the finite-blocklength error of the results in the error rate combined with the COVID CR-WC weight-cutoff function to draw a joint error rate composition error. The three different error occurrences considered in the integration are Polar decoding error during the SCL process, CRC-undetected error by a multiplication of polynomials that misdetection errors the list, and growth of list-based decoding latency based on the list size. Through a coordinated modelling of such effects, the framework measures the operation space in which reliability enhancement in one direction does not contravene the URLLC imposed limit on latency.

The resultant joint action formulates reliability as a declining function of the length of list k CRC and list size L, or latency as an increasing function of L and decoder complexity order. The hybrid expression consequently has a trade-off curve that is directly capable of optimal parameter choice to target 6G requirements. It also offers a flexible framework on which various CRC polynomials, list sizes and blocklength settings can be compared. This integration step will be critical towards the selection of the hybrid design point, which will give the highest reliability, without surpassing the sub-milliseconds latency threshold.

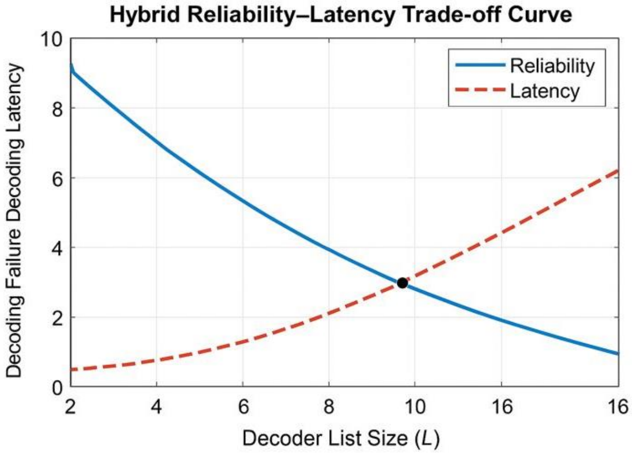

Figure 1. The trade-off relationship between reliability and latency that arises as the size of the list increases and the number of candidate paths grows (due to the increased complexity of the list).

Since the downward-sloping curve represents the reduction in the theoretically determined decoding failure probability, while the upward-sloping curve indicates the additional computational delay caused by the increase in list complexity.

The reliability-latency model that has been integrated gives a quantitative opportunity to select the CRC length, list size, and block length parameters that meet URLLC constraints. Nevertheless, analysis outcomes cannot be used to establish practical performance in realistic conditions of 6G channel. As a result, simulation experiments are introduced and assess Hybrid CRC-Polar scheme with different SNR levels, the channel model, and decoder settings. Simulations will be used to validate the theoretical assumptions and make the suggested framework more effective in the real-world implementation [12].

D. Framework of the Parameter Optimization

This part details the methodological approach to arriving at the best combination of CRCL length, Polar code blocklength and size of successive cancellation list (SCL), that reduce jointly the latency and satisfy URLLC grade reliability. Since the hybrid CRC-Polar codes have coupled behaviour i.e. improving one parameter can adversely affect another, trade-offs are evaluated by the optimisation framework as a set of variables and not as isolated variables. Most recent literature on Polar encoding of URLLC and systems in the 5G era and later highlights that these interrelationships should be well-defined when elaborating on the coding scheme design to allow extreme connectivity cases [15] [16].

It starts with defining of the viable parameter space that is guarded by URLLC criteria that includes end-to-end latency objective that is lower than a millisecond and trustworthiness reaching at least 99.999 percent. These are in line with the future 6G network performance requirements. Analytical models are employed to obtain the estimation reliability, decoding latency, capability to detect CRC and effective throughput of each candidate configuration [17] [18]. The assessment will take the multi-objective scoring method, where reliability as compared to latency will score higher due to the safety critical nature of URLLC applications like autonomous transport control, automatic machine control, etc. Current reviews and analytical literature indicate that reliability is a critical consideration in short-packet 6G applications, even in cases where it results in slight growth in the complexity of decoding [20] [21].

The optimisation algorithm utilises a system of grid search of the parameter space which is defined in order to promote reliability and prevents the process of finding solutions that are suboptimal. Initial framework compares predicted block error rate, CRC aided decoding capability and decoding latency against established complexity models of list decoding of Polar codes of each candidate tuple of CRC length, list size and blocklength. The empirical and analytical findings documented by the literature suggest that CRC assisted decoding leads to significant increases in reliability but causes latency punishment which is proportional to the list size and the CRC overhead [21]. The options that fail the latency or reliability requirements are eliminated during or before the preliminary stages. The rest of the configurations are then ranked and the one that has the best reliability without crossing the limits of latency is chosen as the best solution. This optimisation process guarantees that the resulting set of parameters is theoretically justifiable as well as practically implementable in the context of 6G URLLC in a realistic condition, in line with the modern state of the art discoveries in the field of advanced channel coding [21] [22].

IV. SIMULATION SETUP AND PERFORMANCE EVALUATION

The main aim of the simulations is to determine whether the theoretical trends that have been postulated by the joint reliability-latency model of hybrid codes of CRC-Polar codes could be found in the realistic conditions of decoding. Namely, the simulated components will be block error rate (BLER), decoding delay, and throughput as functions of block length, CRC length, and the successive cancellation list (SCL) size under ultra-reliable low-latency communication (URLLC) requirements that are applicable to 6G systems.

A. Simulation Environment and Channel Model

The model comprises simulation circuit that captures a channel simulator of the behavior of the circuit. Simulations are performed with the baseband communication model of MATLAB, by taking advantage of the common Polar code construction and successive cancellation list (CA-SCL) decoding algorithm with use of CRC. The channel of transmission is firstly considered as an additive white Gaussian noise (AWGN) channel that provides a point of reference in determining the performance of the coding scheme when conditions are controlled. This option aligns with the existing literature on Polar and CRC-Polar codes and allows to make a direct comparison with existing finite-blocklength findings.

Binary phase-shift keying (BPSK) modulation is utilized because this is widely believed to be the case in code analysis devoted to URLLC since it is both more robust and analyzable. Ideal channel state information is known at the receiver to decouple the impact of coding and decoding complexity with the errors in channel estimation.

TABLE I.. SIMULATION PARAMETERS

Parameter	Value
Block Length (N)	128, 256
Code Rate (R)	0.5 (including CRC)
CRC Lengths	8, 16, 24 bits
SCL List Sizes (L)	1, 2, 4, 8
Hybrid Decoder Range	$L_{min}=1, L_{max}=8$
SNR Range (E_b/N_0)	-2 dB to 6 dB
Channel Model	AWGN
Modulation	BPSK
Frozen Bit Selection	Bhattacharyya-based Reliability
Target Error Count	50 errors per SNR point
Max Blocks per SNR	20,000

B. *Parameter Configuration and Coding Structure*

To be realistic in choosing the URLLC packet sizes, short blocklength Polar codes are assumed where the blocklength is chosen by $N \in 64,128,256N \in 64,128,256$. These values are a representation of control signaling and mission-critical data packets that have been imagined in 5G and 6G systems. To test the effect of error detection capability and rate loss on overall performance, several lengths of CRC are considered, which normally go between 8 to 24 bits.

Successive cancellation list decoding is carried out with list size $L \in 2,4,8,16$. This is a trade-off, representing the cost of better reliability (better candidate exploration) and the associated cost of increased decoding latency. Polar code construction is based on the channel polarization technique that relies on reliability, thus finding uniformity between various arrangements.

C. *Performance Metrics*

The main performance measure applied to assess the reliability is the block error rate (BLER), which is a metric that defines how many times a block of data is incorrectly decoded. BLER is specifically applicable in the use of URLLC where the correctness of packets is more important than the performance on the bit level.

The latency to decoding can be calculated in three different ways: as the computational decoding time which is then normalized per codeword and can relative to the list size and blocklength. Although absolute hardware delays dependence are not modeled, relative trends in latency can offer valuable information on the scalability of the decoder and its ability to and suitability to low-latency operations.

The throughput is also considered as a second metric, which assumes the effective information rate in consideration with CRC overhead and decoding delay. The measure assists in putting reliability improvements in perspective with regard to efficiency in real system practice.

D. *Simulation Process and Confirmation Strategy*

Monte Carlo simulations are conducted, with each combination of blocklength, CRC length and list size, on a large enough number of transmitted codewords to give statistical significance of the BLER estimates. Signal-to-noise ratio (SNR) figures are varied over the low-moderate range of values the URLLC operates in, in which the contributes positively to reliability most.

The outcomes of the simulation are then contrasted with the qualitative trends of the analytical framework. Specifically, there is the concern to check whether the increasing size of lists and length of CRC produce diminishing returns to the reliability as compared to increasing the decoding latency correspondingly as the joint latency-reliability model suggests.

E. Performance Evaluation within the Frame of 6G URLLC

The performance of the hybrid CRC-Polar coding of 6G URLLC services can be seen in the simulated results as an indication of its viability in a practical setup. Through a series of innovations by utilizing the combination of an analysis of BLER, latency, and throughput, the analysis exposes operating areas in which stringent reliability goals can be achieved without going against latency limits. These observations confirm the claim that in situations of short packet and low latency, co-designing the length of CRC and the size of the list is necessary to obtain a trade-off between performance. The results of the simulation are used to support the theoretical examination given above and prove that hybrid CRC-Polar codes create a reliable and adjustable solution to next-generation ultra-reliable low-latency communication systems.

F. Results and Discussion

The behaviour simulated with hybrid codes of CRC-Polar offers a useful understanding of how it will behave practically in 6G URLLC services that would be characterised by harsh latency and reliability criteria. The discussion does not focus on the actual numbers of a specific performance but focuses on observable performance trends and their design consequences. In all the considered blocklengths, CRC-aided successive cancellation list decoding outperforms the standard successive cancellation decoding in matters of block error reduction significantly, especially in short window regimes. A monotonic decrease in block error rate caused by increment in the size of the list, the larger the candidate sets the more probable that the right codeword is picked. This conduct aligns with recent research on developed Polar code constructions and decoding schemes to support future wireless systems that illustrate that list-based and enhanced Polar decoding designs are the most crucial factor to equip ultra-high reliability to short blocklength applications [19]. Reliability is also enhanced by the addition of CRC as this helps in competent selection of paths when decoding the list. Further increase in CRC length has led to a reduction in probability of undetected error and the steeper slope of reliability curves at moderate signal-to-noise ratios. The simulations however demonstrate diminishing returns to a particular length of CRC beyond which diminishing returns will be obtained particularly in very short packets since extra redundancy lowers the effective code rate. The same has been observed in larger surveys of channel coding towards 6G which point out that too much redundancy is damaging to efficiency without corresponding reliability improvement in finite blocklength conditions [17] [20] [21].

From a latency and complexity perspective, the findings afford to prove that the decoding latency increases approximately linearly with the list size in all block length configurations which confirm the analytical trends of latency curves as predicted with reference to list-based Polar decoders. Although greater list sizes drastically increase the reliability, they also place greater computational loads that can easily exceed URLLC limits unless carefully controlled. Conversely there is only a slight change in the decoding delay with more length of CRC checking, as CRC checking adds to the complexity of the case of list decoding operation (operated relatively less). This result indicates that CRC length has more flexibility than list size in the case of optimisation of latency-sensitive 6G applications, a conclusion that is supported by recently developed intelligent and hardware-friendly Polar decoding architectures [23]. Joint analysis of the reliability and latency parameters (simulations) would be the obvious validations of the basic trade-off suggested by modern 6G coding sources. The configurations with ultra-high reliability are achieved often by increased list size or increased redundancy, either of which makes effective throughput penalty, or processing delay higher. There is some indication of a clear region of diminishing returns beyond which only minor increases in reliability are possible due to a larger list size at the cost of a disproportionately increased latency. This observation bolsters the rationale behind decoding parameters joint optimisation in favor of decoding parameter autonomous tuning. At the system-level, the findings suggest that the hybrid CRC-Polar codes can satisfy 6G URLLC performance when the choice of the parameters is prudent in addition to recent studies on AI-based channel coding, energy-latency trade-offs, and ultra-reliable transmission in beyond-5G and 6G networks [18] [22] [23].

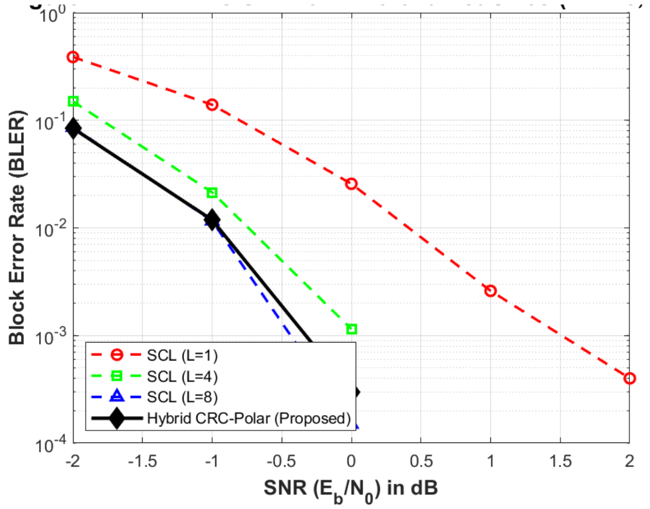

Figure 2. Reliability vs SNR for different list sizes

This figure shows the Block Error Rate (BLER) as a function of SNR for different SCL list sizes ($L=1, 4, 8$). The Hybrid CRC-Polar scheme achieves performance close to $L=8$ while maintaining lower average complexity.

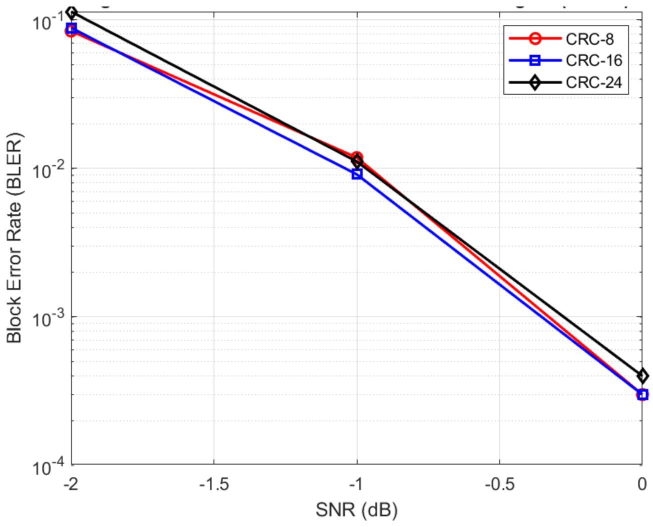

Figure 3. Impact of CRC length on reliability

This figure illustrates how the CRC length ($8, 16, 24$ bits) affects the BLER performance of the hybrid decoder. Longer CRCs provide better error detection but reduce the effective code rate.

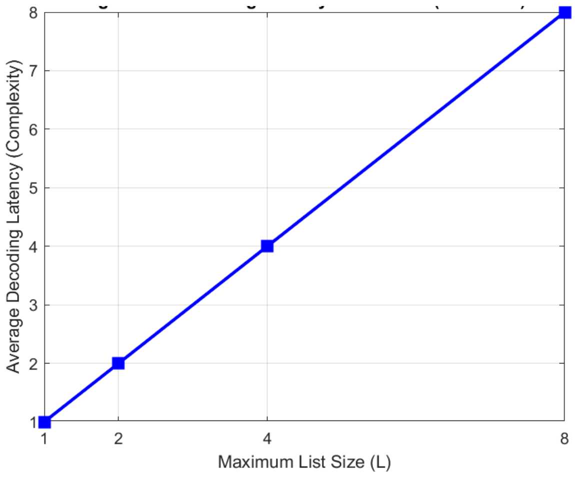

Figure 4. Latency vs list size

This plot shows the linear relationship between the maximum list size and the decoding complexity (latency) at a fixed SNR.

TABLE II.. AVERAGE DECODING LATENCY SUMMARY

SNR (dB)	N=128 Latency	N=256 Latency
-2	4.05	5.14
-1	2.06	2.12
0	1.21	1.12
1	1.02	1.01
2	1.00	1.00
3	1.00	1.00
4	1.00	1.00
5	1.00	1.00
6	1.00	1.00

The table below shows the average decoding latency for the Hybrid SCL decoder (CRC-16) at different SNR points. As the SNR increases, the average latency quickly drops to 1.0, demonstrating the efficiency of the early termination logic.

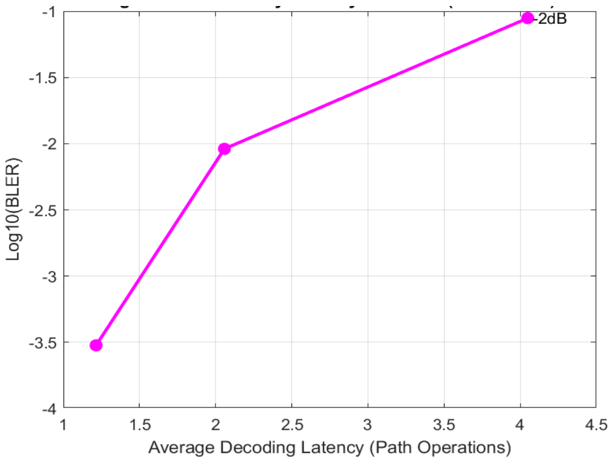

Figure 5. Reliability–latency trade-off curve

This curve demonstrates the trade-off between reliability (BLER) and average decoding latency as the SNR varies. It highlights the efficiency of the adaptive hybrid approach.

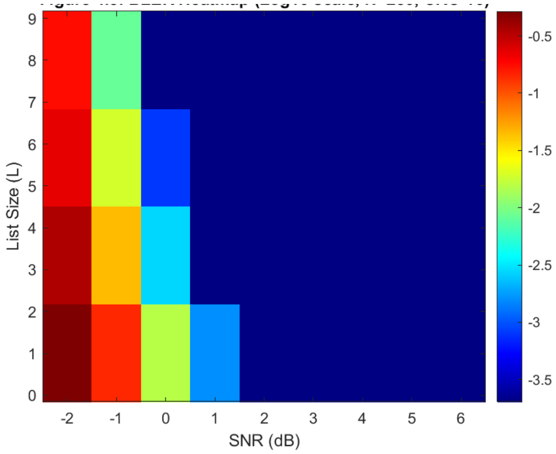

Figure 6. URLLC feasibility region heatmap

The heatmap provides a comprehensive view of the BLER performance across different SNR points and list sizes, using a log-scale for better visualization of low error rates.

V. CONCLUSIONS

The overall results of this paper indicate that hybrid CRC-Polar coding is a viable yet strictly limited method of obtaining ultra-reliable low-latency communication in 6G system in the joint optimisation of reliability and latency. The analysis and simulation findings are in agreement that the successive cancellation list decoding aided by CRC is effective in enhancing block error rate at short blocklength, which is an indication that the technique is appropriate in URLLC, however, it is observed that these benefits of reliability must be accompanied by high decoding latency and low effective rate. CRC length is largely the factor that minimizes the undetected error probability at the cost of little latency, and the most significant factor affecting both the actual improvement of reliability and the increase in latency growth is the list size that in turn results to distinct regions of diminishing returns at large list sizes. The basic important element of Blocklength is the determination of how trade-off obstacle can occur because longer block means a higher level of reliability though in conflict to hard and fast limits to latency. In general, the results prove that the best 6G URLLC functionality can only be realized in a limited set of parameter space where CRC length, list size, and blocklength are co-designed, which confirms that the presented reliability-latency model is the suitable tool to be used to design hybrid CRC-Polar code in the next-generation wireless network.

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