Automorphism Ensemble Polar Code Decoders for 6G URLLC

Understanding the Technology Context

Hans-J. Eisler, Leon Windel

Abstract

Based on the research paper entitled *"Automorphism Ensemble Polar Code Decoders for 6G URLLC"* by the authors Claus Kestel, Marvin Geiselhart, Lucas Johannsen, Stephan ten Brink, and Norbert Wehn, the URLLC scenario in the upcoming 6G standard requires low latency and ultra-reliable transmission. Achieving near-ML performance is challenging, especially for short block lengths. Polar codes are a promising candidate for this application. The mentioned paper discusses the Successive Cancellation List (SCL) decoding algorithm, which provides good error correction performance but at a high computational decoding complexity. The paper introduces the Automorphism Ensemble Decoding (AED) approach, which performs several low-complexity decodings in parallel. This paper presents an AED architecture and compares it to state-of-the-art SCL decoders. Thus given the theoretical and experimental proof-of-principle by Kestel et al., we outline here the position and context of this technical invention protected by a PCT application, managed by the TLB GmbH.

April 18, 2024

1 Summary of the research paper *"Automorphism Ensemble Polar Code Decoders for 6G URLLC"*

The paper titled "Automorphism Ensemble Polar Code Decoders for 6G URLLC," authored by Claus Kestel, Marvin Geiselhart, Lucas Johannsen, Stephan ten Brink, and Norbert Wehn,[1] addresses a critical challenge in the development of the 6th generation (6G) wireless communication standard. This challenge revolves around the need for ultra-reliable low-latency communication (URLLC), which is essential for supporting emerging technologies that require real-time data transmission with minimal errors, such as **autonomous driving, remote surgery, and the Internet of Things (IoT)**.

2 Target

For the market launch of the 6G mobile communication technology, the university is looking for industry partners, licensees and/or investors who can manufacture and deploy such 6G systems. Conceivable are companies with experience in the development and deployment of mobile communication networks or those that have expertise in wireless technology and the necessary infrastructure. Ideal would be players who are familiar with the integration of 6G components, the optimization of network performance, and the large-scale rollout of 6G services.

2.1 Key Concepts Explained

Ultra-Reliable Low-Latency Communication (URLLC): In the rapidly advancing realm of wireless communications, the introduction of Ultra-Reliable Low-Latency Communication (URLLC) marks a transformative leap, especially as we steer towards the next-generation networks - the 6G ecosystem. At its core, URLLC is engineered to meet the exceedingly stringent demands of reliability and responsiveness that are becoming essential in a world increasingly reliant on interconnected and automated systems. The 'Ultra-Reliable' aspect of URLLC refers to its capability to deliver exceptionally high data transmission reliability, targeting error rates as minuscule as one in a million packets. This is not just a technical feat but a critical requirement for applications where even the slightest error can have monumental consequences, such as in autonomous vehicles where a split-second delay or minor miscommunication can lead to critical failures. Similarly, in industrial automation systems, the precision and consistency in communication are paramount, and URLLC's reliability promises to uphold these standards. On the other hand, the 'Low-Latency' characteristic of URLLC aims to achieve groundbreaking transmission speeds, with delays trimmed down to less than a millisecond. This feature is a cornerstone for real-time applications, where immediate responsiveness is non-negotiable, such as in remote surgical procedures or in the real-time control of machinery. By harmonizing ultra-reliability with low latency, URLLC not only caters to the existing demands of high-stakes applications but also paves the way for innovative technologies that will define our future. Its role in the 6G ecosystem is thus not just foundational but also transformational, setting new standards for what is achievable in wireless communication and opening a gateway to an era of unprecedented technological advancements and applications.

Polar Codes: A type of error-correcting code that is Polar Codes represent a significant advancement in the field of error-correcting codes, a technology crucial for maintaining data integrity in wireless communication. Integral to the 5G standard and being keenly considered for 6G, Polar Codes stand out due to their efficiency in correcting errors in data transmission. In the realm of wireless communication, data often traverses through unreliable or noisy channels, where various factors can distort or alter the transmitted information. Error-correcting codes are vital in these scenarios, as they play a crucial role in detecting and rectifying these errors, thus ensuring the reliability of the communication system. Polar Codes, in particular, have been lauded for their unique method of constructing code words, which enables them to achieve high levels of error correction with lower complexity compared to other codes. This makes them highly suitable for the high-speed and high-reliability requirements of modern wireless networks, where data integrity is paramount. As we progress towards more advanced network technologies like 6G, which promise even faster speeds and lower latencies, the role of efficient error-correcting codes like Polar Codes becomes increasingly critical. They not only enhance the overall performance of the network by reducing data loss and retransmissions but also contribute significantly to the robustness and reliability of emerging applications such as IoT, autonomous systems, and other data-intensive technologies that are dependent on the seamless and accurate transmission of vast amounts of data.art of the 5G standard and is considered for 6G due to its efficiency in correcting errors in data transmission. Error-correcting codes help in detecting and correcting errors that occur during data transmission over unreliable or noisy communication channels.

Maximum Likelihood (ML) Performance:Maximum Likelihood (ML) Performance represents the zenith in error correction efficacy that a decoding algorithm can theoretically achieve. In the intricate world of data communication, where every bit of information is crucial, the role of decoding algorithms is paramount in ensuring the integrity and accuracy of transmitted data. ML Performance serves as the gold standard, a benchmark against which the effectiveness of these algorithms is measured. An algorithm that achieves near-ML performance is, in essence, operating at an exceptionally high level of proficiency, correcting errors in transmitted data with remarkable effectiveness. This capability is crucial in today's data-reliant communication networks, where even the slightest error can have far-reaching implications. Achieving near-ML performance means that the algorithm can deftly identify and rectify errors, thereby approaching the best possible outcome in terms of data accuracy and reliability. This is particularly important in applications requiring high precision and reliability, such as in critical communication infrastructures, financial transactions, and healthcare systems. In these scenarios, the near-ML performance of decoding algorithms not only enhances the overall efficiency and reliability of the communication system but also plays a vital role in maintaining the trustworthiness and security of the data being transmitted.st performance in terms of error correction that can be achieved by a decoding algorithm. Achieving near-ML performance means that the algorithm can correct errors in transmitted data very effectively, approaching the best possible outcome.

Successive Cancellation List (SCL) Decoding stands out as a pivotal decoding algorithm for Polar Codes, acclaimed for its superior error correction capabilities. This algorithm is a cornerstone in the domain of data transmission, particularly when leveraging the strengths of Polar Codes within modern communication systems. However, the very attributes that make SCL Decoding highly effective in error correction also introduce notable challenges. Primarily, it demands significant computational resources, which translates into a trade-off between performance and system efficiency. This substantial computational requirement leads to higher latency in data processing, a critical factor in time-sensitive applications and contrary to the low-latency objectives of advanced communication technologies like 5G and the upcoming 6G. Furthermore, SCL Decoding's extensive resource utilization has implications on the efficiency of the system, particularly in terms of area and energy consumption. This aspect is increasingly important in an era where energy efficiency and minimization of hardware footprints are crucial for sustainable technological development. As such, while SCL Decoding offers robust error correction, its adoption and implementation within communication systems necessitate a balanced approach, weighing its high correction proficiency against the increased latency and resource demands, especially in scenarios where efficiency and speed are of paramount importance.

The Innovation: **Automorphism Ensemble Decoding (AED)**
The paper introduces a groundbreaking decoding technique, Automorphism Ensemble Decoding (AED), as a robust solution to the limitations inherent in the Successive Cancellation List (SCL) decoding algorithm. This innovative approach, AED, is strategically designed to enhance error correction capabilities, a crucial aspect in the realm of data transmission, especially when dealing with the intricacies of Polar Codes. What sets AED apart is its ability to significantly mitigate the computational complexity that typically characterizes SCL decoding. By doing so, AED addresses one of the fundamental challenges in advanced communication systems: balancing error correction efficiency with system performance. A notable reduction in computational complexity directly translates to lowered latency, a critical factor for applications that depend on real-time data processing and rapid response times. Additionally, AED's streamlined approach results in lower energy consumption, aligning with the growing need for energy-efficient technologies in today's increasingly digital and environmentally conscious world. This dual ad-

vantage of enhanced error correction, coupled with reduced computational demand, positions AED not just as an alternative, but as a potentially superior decoding technique, particularly in high-performance communication networks where both accuracy and efficiency are paramount. The introduction of AED marks a significant step forward in decoding technology, potentially revolutionizing the way we approach error correction in complex communication systems.

The paper introduces an advanced decoding technique called **Automorphism Ensemble Decoding (AED) as a solution to the limitations of the SCL decoding algorithm**. AED is designed to improve error correction capabilities while significantly reducing the computational complexity, latency, and energy consumption.

Here's how it works and why it's important: Parallel Decoding: Unlike SCL, which processes data sequentially, AED performs multiple low-complexity decodings in parallel. This parallel processing approach significantly reduces the time it takes to decode the transmitted data, thereby lowering latency. Advanced Path Metric Based Candidate Selection: AED incorporates a sophisticated method for selecting the most likely correct decoding paths out of several possibilities. This reduces the complexity of the implementation and the resources needed for decoding.

Efficiency Gains: The paper's findings show that the AED architecture outperforms state-of-the-art SCL decoders in terms of *latency* (**up to 4.4 times faster**), *area efficiency* (**up to 8.9 times more efficient**), and *energy efficiency* (**up to 4.6 times more efficient**), all while maintaining or even improving error correction performance.

3 Integration into 6G Standard

In the emerging 6G ecosystem, Ultra-Reliable Low-Latency Communication (URLLC) is poised to play a foundational role, underpinning a vast array of applications where high reliability and low latency are not just desirable, but essential. This technology is particularly critical in sectors such as **industrial automation**, where processes in manufacturing and robotics demand precise timing coupled with unwavering reliability. Here, even the smallest delay or error can lead to significant disruptions, making the ultra-reliable and low-latency nature of URLLC indispensable. In the realm of **autonomous systems, including vehicles and drones**, URLLC becomes even more crucial. These systems rely on real-time data to make split-second decisions, where any delay can have serious consequences. The implementation of URLLC ensures these systems receive timely and accurate data, enhancing their decision-making capabilities and overall safety. Furthermore, mission-critical services such as **emergency response, disaster management, and critical infrastructure monitoring** stand to benefit significantly from URLLC.

4 Location in the 6G Technology Stack

In the architecture of 6G technology, Ultra-Reliable Low-Latency Communication (URLLC) is seamlessly integrated across the entire network stack[2], showcasing its indispensable role in shaping the future of wireless communications.[2] This integration spans from the core network elements to the edge, ensuring that every layer of the network contributes to and benefits from the URLLC paradigm.[4]

At the **Radio Access Network (RAN) level**, cutting-edge innovations such as massive MIMO (Multiple Input Multiple Output) and advanced modulation schemes are pivotal. These technologies are specifically tailored to meet the stringent requirements of URLLC, enhancing signal strength and quality, thus ensuring reliable and consistent communication even in densely populated or traditionally challenging environments.

In the core network, the implementation of URLLC is further bolstered by advanced networking technologies like Software-Defined Networking (SDN) and network slicing. SDN introduces a new level of flexibility and control, enabling dynamic management of network resources to prioritize URLLC traffic, thereby enhancing reliability. Network slicing, on the other hand, allows for the creation of dedicated virtual networks, each configured to meet specific URLLC demands, ensuring that critical applications receive the bandwidth and speed they require without interference.

Edge computing represents another critical aspect of the 6G URLLC ecosystem.[6] By decentralizing data processing and bringing it closer to the data source, edge computing drastically reduces latency, a core tenet of URLLC. This is particularly vital for applications requiring real-time processing and decision-making, as it minimizes the time taken for data to travel between the source and the processing unit. This reduction in latency not only complements but significantly enhances the overall goal of URLLC, ensuring that communications are not just reliable, but also extraordinarily swift.

Overall, the location of URLLC technologies within the 6G technology stack signifies a holistic approach to network design. By embedding URLLC capabilities at every level of the network, from the core to the edge, 6G architectures are being tailored to support a future where fast, reliable, and efficient communication is not just a benefit but a necessity for a myriad of applications and services.

References

[1] Claus Kestel, Marvin Geiselhart, Lucas Johannsen, Stephan ten Brink, Norbert Wehn, Automorphism Ensemble Polar Code Decoders for 6G URLLC, arXiv:2303.01235, https://doi.org/10.48550/arXiv.2303.01235 1

[2] Petar Popovski, Čedomir Stefanović, Jimmy J. Nielsen, Elisabeth de Carvalho, Marko Angjelichinoski, Kasper F. Trillingsgaard, Alexandru-Sabin Bana, Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC), arXiv:1810.06938 4

[3] Kerim Gökarslan, Achieving Ultra-Reliable Low-Latency Communication (URLLC) in Next-Generation Cellular Networks with Programmable Data Planes, arXiv:2309.09079

[4] Maraj Uddin Ahmed Siddiqui and Hanaa Abumarshoud and Lina Bariah and Sami Hakam Muhaidat and Muhammad Ali Imran and Lina S. Mohjazi, URLLC in Beyond 5G and 6G Networks: An Interference Management Perspective, IEEE Access, 2023, 11, pp.54639-54663 4

[5] Iulisloi Zacarias and Francisco Carpio and André Costa Drummond and Admela Jukan, Optimum Network Slicing for Ultra-reliable Low Latency Communication (URLLC) Services in Campus Networks,2023 19th International Conference on the Design of Reliable Communication Networks (DRCN), 2023, pp.1-8, https://api.semanticscholar.org/CorpusID:258335972

[6] Junaid Nawaz Syed and Shree Krishna Sharma and Mohammad N. Patwary and Mohammad Asaduzzama, Enhanced URLLC-Enabled Edge Computing Framework for Device-Level Innovation in 6G, https://api.semanticscholar.org/CorpusID:233886186 4