Design of a Semantic-Aware New Radio PUSCH Encoder for enhanced mobility

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***Abstract*— This paper introduces an adaptive semantic-aware communication system designed to enhance the efficiency and reliability of future mobile networks under diverse mobility settings. The proposed system leverages adaptive Orthogonal Frequency Division Multiplexing (OFDM) numerology and flexible Demodulation Reference Signal (DMRS) configurations, to optimize uplink transmission based on the contextual significance of data. This approach is crucial for mitigating the effects of Doppler spread associated with high mobility ensuring robust performance in diverse scenarios. By dynamically adjusting the Physical Uplink Shared Channel (PUSCH) DMRS configurations in response to user velocity, the system maintains high communication reliability and resource efficiency. Our simulations validate the potential of the proposed approach linking variations in Signal-to-Noise Ratio (SNR) and Block Error Rate (BLER) to different velocities and demonstrating significant improvements across various velocities. The results highlight the importance of adaptive strategies in OFDM numerology and subcarrier spacing adjustments to overcome Doppler challenges, as well as the benefits of dynamically adjusting DMRS signals to improve throughput and resource efficiency by reducing unnecessary signaling overhead.**

Keywords*— *Semantic encoder, OFDM numerology, DMRS, Doppler spread, SNR, BLER.

I. Introduction

The rapid evolution of mobile communication networks, driven by advancements in 5G technologies [1], has significantly increased the demand for high reliability, efficiency, and adaptability in diverse and dynamic mobility environments. The proliferation of connected devices and the integration of various demanding applications necessitate advanced communication systems capable of meeting these stringent requirements. In the current generation of communication systems, demanding Key Performance Indicators (KPIs) related to high throughput, low latency, increased reliability and mobility for 5G users have been addressed through the introduction of novel technology components. These include: a) the development of massive MIMO schemes that enhance spectral efficiency and reliability utilizing multiple antennas, b) the development of components that enable the operation of networks at higher spectrum bands allocating more bandwidth to users achieving increased data rates, c) the design of novel signal processing techniques supporting beamforming and beam steering that redirect signal energy precisely towards the user enhancing signal strength.

However, as we migrate from 5G to 6G systems additional considerations, beyond simple KPI improvement, include key societal values related to environmental, security, and economic sustainability. Towards this direction, the concept of *semantic communications* has been proposed as a key enabling technology to address both performance and value indicators of 6G services [2]. Semantic communications aim to exploit service-specific and content-specific information to optimize communication systems. In contrast to previous generations of communication systems that have been primarily designed to "accurately and effectively transmit symbols" (i.e., maximize throughput) [3], semantic communications focus on the successful exchange of semantically important information. Therefore, semantic communications leverage the context and meaning of the transmitted information to optimize network performance.

Recognizing the great potential of semantic communications in beyond 5G and 6G systems, several studies have been proposed optimizing these systems from different perspectives. For example, in [4] the authors explore the use of semantic encoders to dynamically adjust Hybrid Automatic Repeat Request (HARQ) protocols, while in [5] an adaptive modulation and retransmission scheme is proposed to maximize spectral efficiency. Another study [6], introduces a framework leveraging deep neural networks for adaptive encoding and decoding of semantic information, optimizing transmission based on channel conditions. Finally, a recent survey of the topic is summarized in [7]. The main limitation of these studies is that they do not take into consideration the specificities of the 5G/6G protocols stack during the design of the corresponding semantic encoders/decoders that are defined by the relevant standardization bodies. One of the first studies directly applying the concept of semantic communications in 5G/6G networks has been presented in [8].

In the present study, we enhance the state of the art in semantic communications through the development of semantic encoders/decoders optimizing the frame structure and PHY layer procedures in the New Radio (NR) protocol stack, as defined in [9], [10] and [11]. According to these standards, the NR frame structure has been designed to be

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flexible supporting: a) adaptive numerologies and, b) dynamic Demodulation Reference Signals (DMRS) configurations. The ability of the NR system to dynamically adapt the numerology, enables the adjustment of subcarrier spacing and symbol duration based on the propagation conditions and mobility, thus ensuring optimal performance across diverse scenarios. In addition to this, the strategic adjustment of DMRS configurations plays a vital role in channel estimation, which is essential for coherent demodulation of the uplink signal. The system effectively mitigates the adverse effects of Doppler spread, which can cause significant signal degradation at high speeds, through dynamic configuration of the DMRS in accordance to the user velocity.

In response to these observations, we develop a real-time semantic encoder that categorizes data based on contextual significance and dynamically adjusts key communication parameters to optimize performance, such as Orthogonal Frequency Division Multiplexing (OFDM) numerology and DMRS configurations, considering the changing requirements of applications and the channel conditions. This adaptive strategy aligns with the evolving standards and demands of 6G systems, ensuring high signal integrity and communication reliability even under challenging mobility conditions.

Our comprehensive simulation analysis confirms the effectiveness of the proposed system by mapping the relationship between Signal-to-Noise Ratio (SNR) variations and Block Error Rate (BLER) fluctuations at various user velocities. Specifically, the simulations show how adaptive OFDM numerology and subcarrier spacing adjustments can overcome Doppler challenges, and how dynamic DMRS adjustments can improve resource efficiency by reducing unnecessary signaling. Additionally, this adaptive system effectively manages the level of overhead by reducing it at low speeds and increasing it at high speeds. At lower velocities, the system minimizes the required overhead by limiting the amount of control signaling needed, thereby optimizing resource usage. Conversely, at higher velocities, where the Doppler effects are more pronounced, the system increases the overhead to ensure robust channel estimation and reliable communication. This dynamic management of overhead ensures that the system can maintain high performance and reliability across a wide range of mobility scenarios, ultimately leading to a more efficient and effective mobile communication network.

The remainder of this work is organized as follows: In Section 2, we delve into the Physical Layer Overview, detailing the adaptive numerology and flexible DMRS configurations essential for robust performance in varying mobility scenarios. Section 3 introduces the NR Semantic Encoder, discussing its role in optimizing various communication parameters based on contextual significance and real-time conditions. Following this, Section 4 details the Simulation Initialization and Setup, with Section 5 analyzing the performance evaluation. Finally, Section 6 concludes the paper, summarizing the key findings and highlighting the effectiveness of the proposed system in various mobility scenarios.

II. Physical Layer Overview

The physical layer architecture of the system is designed with a comprehensive focus on achieving high efficiency and reliability in communications, even when faced with the significant challenges posed by diverse user mobility patterns. By integrating advanced technologies and adaptive system optimization mechanisms, the network solution ensures robust performance under varying operating conditions. This section provides an overview of the basic principles and architectural features that enable dynamic adjustments of the Physical Uplink Shared Channel (PUSCH) DMRS configurations, alongside adaptive strategies in OFDM numerology and subcarrier spacing. These components play a significant role in mitigating Doppler effects and maintaining seamless network connectivity and reliability.

A. Adaptive Numerology

In 5G NR, the downlink transmission waveforms use conventional OFDM with a Cyclic Prefix (CP). Similarly, the uplink transmission waveforms utilize OFDM with CP but incorporate an optional transform precoding function, specifically the Discrete Fourier Transform (DFT) spreading, that can be dynamically enabled or disabled. In scenarios involving shared spectrum channel access within Frequency Range 1 (FR1), the subcarrier mapping for the uplink transmission waveform can be allocated to subcarriers across one or more physical resource block (PRB) interlaces. In other words, the subcarriers can be distributed among different PRBs, enhancing spectrum utilization efficiency [12]

To accommodate a broad spectrum of carrier frequency bands (ranging from sub-1 GHz to mmWave bands) and to meet the varying requirements of different use cases and deployment scenarios, 5G NR employs a flexible and scalable numerology with subcarrier spacing as defined in [9]. Consequently, the subcarrier spacing is given by the equation $\Delta f = 2^{\mu} \times 15\ kHz$, resulting in Δf values of 15, 30, 60, 120, 240, 480, and 960 kHz for μ = 0, 1, 2, 3, 4, 5, and 6, respectively. The use of different subcarrier spacings, results in shorter slot durations in the time domain, which enhances the system’s flexibility and adaptability to various use cases and deployment scenarios. The NR frame structure in the time domain consists of 10 ms radio frames being divided into 10 subframes of 1 ms each. These subframes are further divided into slots, with the number of slots per subframe determined by the subcarrier spacing. A Physical Resource Block (PRB) is defined as 12 consecutive subcarriers in the frequency domain and consists of multiple Resource Elements (Res), where each RE is the smallest unit and comprises one subcarrier in the frequency domain and one OFDM symbol in the time domain (Fig. 1)

In 5G NR, adaptive subcarrier spacings and advanced transmission techniques maintain orthogonality among

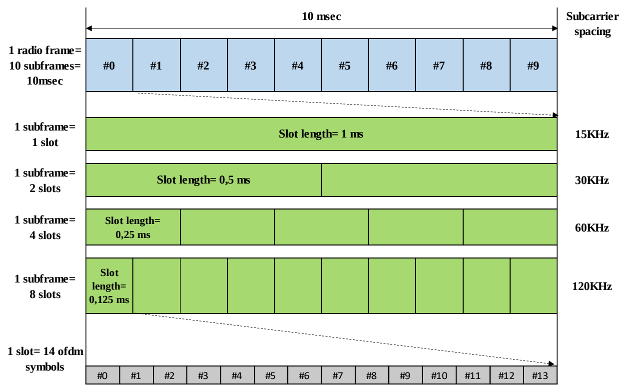

Fig. 1. 5G NR Frame structure

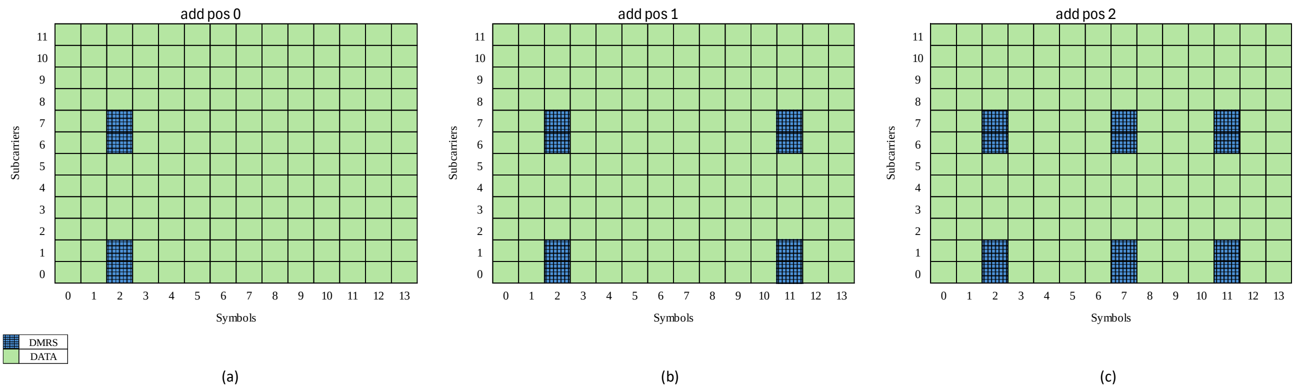

Fig. 2. DMRS Configuration Type 2 with a) 0, b) 1 and c) 2 aditional DMRS respectively

subcarriers, crucial for robust performance in varying mobility scenarios. Larger subcarrier spacings in high mobility environments reduce OFDM symbol durations, mitigating intercarrier interference (ICI) caused by high Doppler drifts, to ensure signal integrity.

B. *Flexible DMRS Configurations*

In 5G NR, the PUSCH is the primary channel that carries user data from the User Equipment (UE) to the base station (gNodeB). PUSCH handles various types of data, including voice, video, and internet browsing information, accommodating different Quality of Service (QoS) requirements. The efficient transmission of this data relies on advanced techniques like Adaptive Modulation and Coding (AMC), HARQ, and MIMO. These techniques help optimize data rates, enhance reliability, and improve link performance by adapting to the prevailing channel conditions and leveraging spatial diversity.

A critical aspect of PUSCH operation is the use of reference signals, specifically the DMRS. DMRS is instrumental for channel estimation, which is essential for the coherent demodulation of PUSCH. By providing known reference sequences, DMRS allows the receiver to accurately estimate the channel characteristics, compensating for impairments such as multipath fading and Doppler shift. This precise channel estimation ensures that the transmitted data can be correctly demodulated at the receiver, maintaining the integrity and reliability of the communication link.

Efficient resource utilization and throughput optimization in modern communication systems are further enhanced by the dynamic adjustment of DMRS configurations. This approach reduces the allocation of resource blocks for reference signals, thereby freeing up resources for data transmission and minimizing signaling overhead. The adaptive adjustment of DMRS is crucial, especially in relation to channel characteristics, where higher fluctuation rates in the frequency domain and rapidly varying channels in the time domain necessitate denser DMRS allocations. Striking a balance between channel estimation accuracy and DMRS overhead is essential for optimizing throughput while ensuring reliable channel tracking. The New Radio (NR) standard supports configurable reference signals tailored to specific UE conditions, accommodating diverse propagation environments and varying mobility levels. This adaptability is pivotal for maintaining high performance and efficient resource utilization, ensuring accurate channel estimation across different mobility scenarios.

Specifically, the DMRS is adapted to the conditions of each UE, featuring configurable frequency-domain patterns and time-domain densities. Configuration type 1 specifies a denser arrangement, with six subcarriers per physical resource block (PRB) per antenna port, utilizing alternate subcarriers. In contrast, configuration type 2 employs a sparser pattern, with four subcarriers per PRB per antenna port, organized into two groups of two consecutive subcarriers. For the time-domain, configurations include at least one front-loaded DMRS symbol per slot for low mobility scenarios, with up to three additional symbols for high mobility conditions, ensuring precise channel estimation and efficient resource utilization.

III. NR SEMANTIC PUSCH ENCODER

The core component of the NR system is the semantic encoder that classifies data based on contextual significance and dynamically adjusts the non real-time and the near-real time communication parameters of PUSCH to optimize the performance of the system. This includes the OFDM numerology and the DMRS configurations mentioned above along with the scheduling priorities. The relevant decisions are taken considering the semantics of the applications, the mobility of UEs and the dynamically changing channel conditions.

A schematic diagram of the NR semantic encoder is depicted in Fig. 3. The semantic encoder follows the Shannon and Weaver's reference architecture [13] decomposed into the effective, semantic and technical layers. The effective layer gathers applications' goals and objectives and tries to address their requirements in terms of Key Value Indicators (KVIs) and KPIs by prioritizing high and low priority bit streams. Information data of high significance, such as critical sensor readings, are appropriately encoded to ensure optimal transmission with high reliability and low latency. Conversely, lower-priority data, like non-urgent updates, are encoded to be transmitted with more relaxed parameters, at a later stage, in order to enhance the overall resource efficiency. This approach ensures that critical applications receive the necessary resources for optimal performance, while non-critical data do not unnecessarily burden the system.

To achieve this, in addition to application requirements the effective layer collects measurements from the system enriching its knowledge base with statistics related to UE mobility, received signal strength and channel quality, power consumption, throughput per slice etc. These measurements are collected through the O1 interface O-RAN which can be then used by the Non Real time (Non-RT) RIC controller to

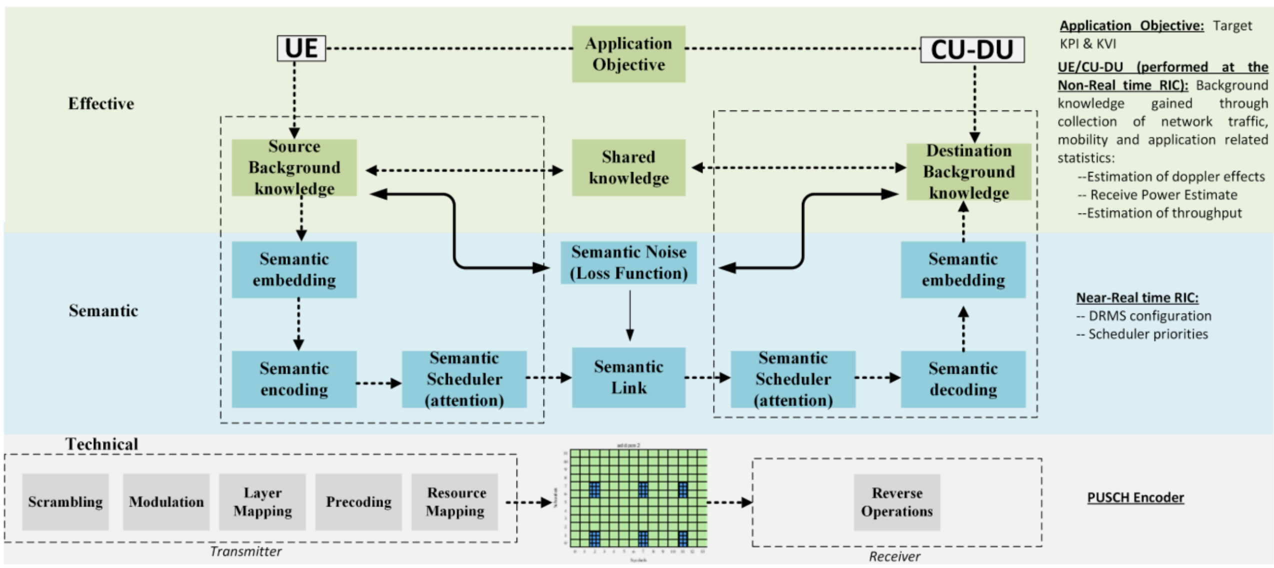

Fig. 3. Semantic NR PUSCH Encoder

train machine learning models estimating the main physical parameters of the NR system such as the Doppler effect, the throughput, the semantics of bit streams etc.[14]

The semantic layer then uses this information to adapt the system parameters based on different speeds and mobility patterns, maintaining consistent performance independent of whether the UE is stationary, moving slowly, or traveling at high velocity. By leveraging the flexible and scalable numerology of 5G, the encoder dynamically selects subcarrier spacing based on real-time mobility patterns, application requirements, and channel conditions. For high-mobility or critical scenarios, larger subcarrier spacings are chosen to mitigate Doppler effects and maintain signal integrity. In low-mobility or stationary scenarios, smaller subcarrier spacings are used to enhance spectral efficiency. This adaptive approach ensures robust performance under varying mobility and channel conditions. The relevant decisions are taken by the Neal-RT RIC creating a configuration file for the radio resource configuration (RRC) protocol optimizing the DMRS density and pattern according to channel variability, data importance, and evolving application requirements. In the time domain, the DMRS patterns are strategically placed within transmission slots to adapt to mobility conditions. For high-mobility scenarios, DMRS symbols are inserted more frequently to improve channel tracking. Conversely, for low-mobility or stable conditions, fewer DMRS symbols are used, reducing overhead and freeing up resources for data transmission. This dynamic adjustment balances channel estimation accuracy with efficient resource utilization, ensuring that only the necessary signaling is used, optimizing the signaling overhead, and improving overall system throughput.

This approach ensures that critical applications receive the necessary resources for optimal performance, while minimizing unnecessary burden on the system for non-critical data. The system's ability to dynamically adjust based on application requirements and channel conditions highlights its potential to meet the diverse and evolving needs of future networks. In addition to DMRS configuration, the semantic encoder also selects appropriate weights for the uplink scheduling that are applied at the "layer mapping" block of the PUSCH encoder shown in the technical layer of Fig.3.

IV. Simulation Initialization and Setup

To validate the effectiveness of the proposed real-time semantic encoder, extensive simulations were conducted across various mobility scenarios, channel conditions, and data significance levels. The performance metrics considered focused on SNR and BLER.

In our simulations, various OFDM subcarrier spacings (15, 30, 60, and 120 kHz) have been considered. These tests were conducted under different mobility and channel conditions to evaluate and optimize the system's performance. To understand how the system behaves under diverse scenarios, ensuring robust and efficient communication across a range of environments and mobility levels, the subcarrier spacing was varied.

On the other hand, in 5G NR, PUSCH mapping is categorized into Type A and Type B [9], [11]. For Type A, the DMRS is fixed at the 3rd or 4th symbol of the PUSCH allocation, and the PUSCH transmission starts at symbol 0. The length of PUSCH transmission ranges from 4 to 14 symbols for normal CP and from 4 to 12 symbols for extended CP. In contrast, Type B places the DMRS at the first symbol of the PUSCH allocation. Here, the PUSCH can start at any symbol from 0 to 13 for normal CP and from 0 to 12 for extended CP, with a PUSCH length ranging from 1 to 14 symbols for normal CP and from 1 to 12 symbols for extended CP. In our simulation, we used PUSCH mapping Type A with length of 14 symbols and fixed DMRS position as in Figure 2 and a consistent starting point at symbol 0 for PUSCH transmission. In addition, DMRS schemes (0, 1, and 2 additional DMRS positions) at different speeds were used, to enhance performance under various conditions.

The parameters of our simulations are detailed in Table 1, including various OFDM subcarrier spacings, DMRS configurations, UE's velocities and other relevant settings.

TABLE 1: SIMULATION PARAMETERS

Parameter	Value
Carrier Frequency (GHz)	3.5 Ghz
Modulation	16QAM
CSI	Imperfect (estimated)
Subcarrier Spacing (KHz)	15, 30, 60, 120
PUSCH mapping	Type A
PUSCH duration	14 symbols
DMRS Configuration type	2
Additional DMRS	0, 1, 2
DMRS length	1
Detector	LMMSE
SNR Range	0-10
UE's speed (km/h)	10, 100, 300, 500

V. PERFORMANCE EVALUATION

Our results indicated significant improvements in BLER for high-priority data, particularly in high-mobility and varying channel conditions. The encoder's dynamic adjustments to OFDM numerology and DMRS configurations effectively mitigated Doppler shifts and adapted to channel variations, ensuring reliable data transmission even at high speeds. This capability underscores the encoder's effectiveness in maintaining signal integrity and communication reliability under diverse operational conditions.

Specifically, the analysis of various DMRS configurations, as depicted in Fig. 4, indicates that at lower mobility speeds, such as 10 km/h, the addition of DMRS actually results in a higher BLER. This suggests that the extra overhead introduced by additional DMRS may not be beneficial in relatively stable channel conditions, where the necessity for frequent adjustments is minimal. The increased BLER in these scenarios, points to the possibility that the additional DMRS might introduce unnecessary complexity and overhead, leading to less efficient communication. However, the situation changes significantly as the speed increases. At higher mobility speeds, such as 100 km/h and 300 km/h, the additional DMRS configurations demonstrate a clear advantage. The data shows that at higher speeds, the additional DMRS helps to effectively counteract the adverse effects of Doppler shifts and channel variations, resulting in improved signal reliability and lower BLER. This highlights the encoder's ability to adapt dynamically to varying mobility conditions, ensuring robust performance even in challenging environments.

Proceeding further, our study examined the impact of different subcarrier numerologies under varying speed scenarios with a fixed SNR of 6 db (Fig. 5). The performance analysis reveals that at lower speeds (10 km/h and 100 km/h),

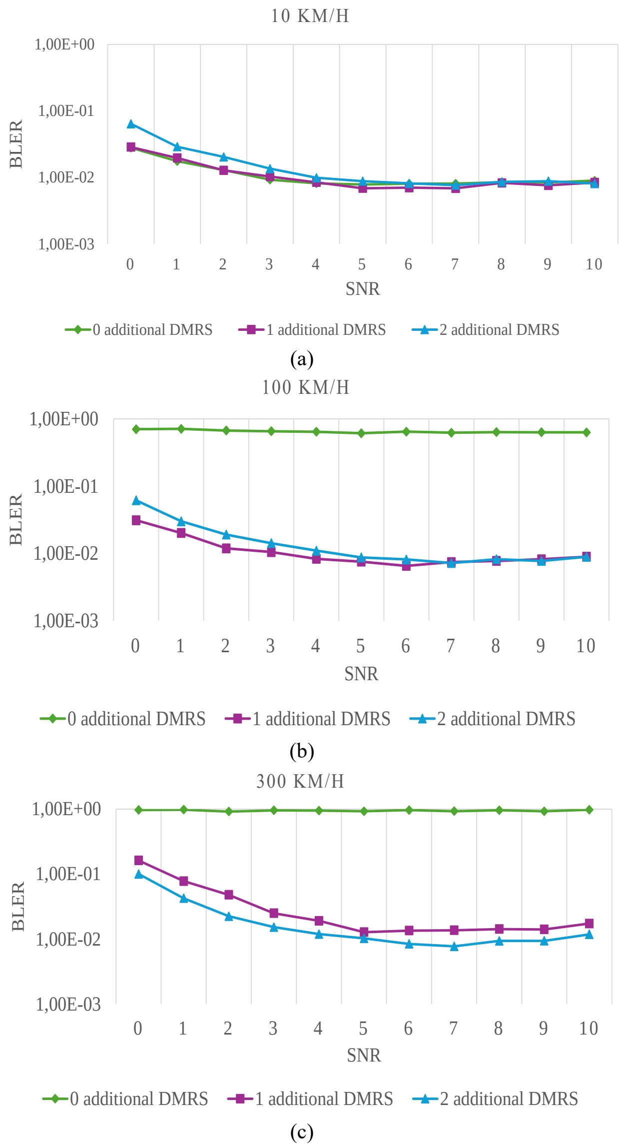

Fig. 4. BLER vs. SNR (dB)- Additional DMRS evaluation results

the 15KHz subcarrier spacing exhibits the lowest BLER, demonstrating its robustness to slow-moving UEs. However, at higher speeds (300 km/h and 500 km/h), the BLER for 15KHz increases sharply, indicating its limitations. Conversely, higher subcarrier spacings such as 30KHz, 60KHz, and 120KHz demonstrate improved performance at these speeds, with 60KHz and 120KHz particularly effective at very high speeds (500 km/h). This analysis highlights the importance of selecting appropriate numerologies based on the speed of the UE in order to optimize the system performance, adopting lower numerologies for low speeds and higher numerologies for high speeds to effectively address rapid Doppler shifts and channel variability.

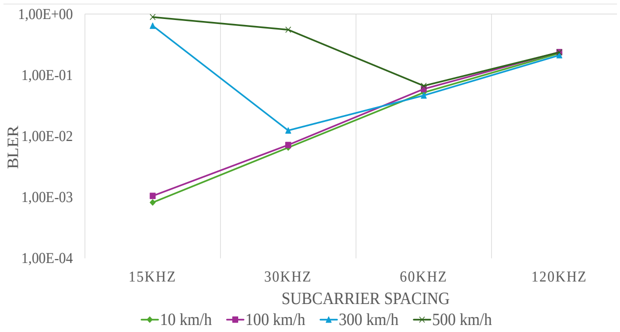

Fig. 5. BLER vs. SNR (dB)- evaluation results, using different subcarrier spacing at various speeds

VI. CONCLUSION

In conclusion, our study demonstrated significant advancements in semantic communications for future networks through the development of adaptive semantic encoders and decoders. By optimizing the NR protocol stack's frame structure and physical layer procedures, we achieved enhanced signal integrity and communication reliability, particularly in high-mobility environments. Our simulations confirmed that adaptive OFDM numerology and DMRS configurations are crucial for mitigating Doppler effects and maintaining robust performance across diverse mobility scenarios. Furthermore, the contextual adaptation of communication parameters ensured that critical applications received optimal resources while effectively managing the trade-off between resource efficiency and communication reliability. This adaptability highlights the potential of semantic communications to enhance network performance, while also addressing broader challenges such as scalability, user experience, and operational efficiency. The findings lay a strong foundation for future research in intelligent, context-aware communication strategies, paving the way for more efficient, reliable, and sustainable 6G networks.

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