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Dynamic IRS Selection for High-Speed Mobility in 6G Networks

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Abstract: The Intelligent Reflecting Surfaces (IRS) have become a promising technology in the enhancement of wireless communication by providing programmable control of the propagation environment. Most of currently available IRS-assisted systems are however designed under quasi-static conditions of the channel, which may not be suitable for high-mobility scenarios envisioned in future 6G networks. This paper proposes a Doppler-aware IRS performance evaluation framework for high-mobility scenarios.A channel model which includes Doppler frequency is developed to accurately represent the impact of user mobility on signal propagation. Under high mobility, the proposed scheme is able to effectively recover from the channel degradation caused by Doppler effect.The behavior of the proposed scheme is analyzed based on the large-scale Monte Carlo simulation in the parameters of Bit Error Rate (BER) and achievable rate under different signal-to-noise ratios and user velocities up to 250 km/h. The simulation results have shown that the dynamic IRS scheme performs significantly better than both the conventional static IRS and non-IRS system, with significantly lower BER and higher achievable rates in all the tested conditions. These results indicate the suitability of the proposed approach in ensuring stable and highly efficient communication in high-mobility settings, thus making it an excellent choice in next-generation 6G wireless systems.

Keywords: Intelligent Reflecting Surface (IRS), 6G, High Mobility, Doppler Effect, Dynamic IRS, Phase Adaptation, Bit Error Rate (BER), Achievable Rate.

I. INTRODUCTION

In rapidly changing environments, the need for ultra-reliable, high-capacity, low-latency connectivity is the key for evolution towards sixth generation (6G) wireless communication systems [5], [11]. Under extreme mobility conditions, communication performance have to be reliable,such as those in emerging applications like high-speed vehicular communication, intelligent transportation systems and real time immersive services. But using high-frequency bands like millimeter-wave (mmWave) poses a number of challenges, such as high path loss, high signal blockage and fast channel variation, thus affecting communication reliability [17]. This challenges highlight the importance of sophisticated technologies that can intelligently modify and control the wireless propagation environment.Recently, Intelligent Reflecting Surfaces (IRS) have shown great potential [7],[13] in effectively boosting wireless communications performance without incurring high costs or more energy consumption. The IRS consists of multiple passive reflecting components and can dynamically change the phase of the incident electromagnetic waves at the input to direct reflected signal towards desired direction at the output. The introduction of controllable propagation path between the base station and user equipment will fully enhance the signal strength, coverage, and spectral efficiency [15]. Instead of using traditional active relay approaches that rely on radio frequency chains and amplification, IRS requires no active RF chains, making it ideal for sustainable and "green" 6G solutions.

Although these benefits exist in the existing IRS-assisted communication systems which are designed under either the static or quasi-static channel assumption, in which the CSI is relatively fixed over time. High-mobility scenarios, on the other hand, are characterized by channel variations caused by Doppler effect as a result of user movement, which are not valid under such assumptions. For this reason, the computed time-varying phase shifts cause misalignment and degrade the performance of using traditional static IRS schemes. Thus, the performance of IRS is still constrained in high-speed scenarios and there is a vital requirement for mobile-aware IRS frameworks capable of implementing mobility-aware adaptive IRS operation to tackle dynamic channel conditions.

To overcome this challenge, this paper suggests a mobility-adaptive dynamic IRS selection and phase optimization scheme for high-speed wireless communication systems. The incorporation of Doppler frequency in a time varying channel model is assumed to model the effect of user mobility on signal propagation. The proposed framework models the impact of Doppler shift on IRS-assisted communication and compares static vs. Doppler-compensated IRS

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schemes. The suggested method models the Doppler effect on channel gain and thus reduces the Doppler-induced degradation to performance.To assess the performance of the proposed framework, a large number of simulation runs are performed, with the Bit Error Rate (BER) and the achievable rate under various signal-to-noise ratios and velocities calculated. The results show that the proposed dynamic IRS scheme is clearly superior to the conventional static IRS and non-IRS schemes as it has higher reliability and spectral efficiency even at high speeds. The results demonstrate how dynamic IRS can become a promising solution for the realization of strong and efficient communication in future high-mobility scenarios in the 6G era.

II. LITERATURE REVIEW

Intelligent Reflecting Surface (IRS)-assisted wireless communications have yielded promising results for enhancing spectral efficiency, coverage, and energy efficiency in future wireless networks. Building blocks of the IRS-enabled communication have been developed, which have proved its capacity of effectively controlling the wireless propagation medium and improving the signal quality over the performed communication compared to a conventional relay-based communication scheme [7],[13]. The works demonstrate the possibility of achieving high performance of communication with minimal hardware complexity by using IRS.Research on performance analysis and optimization of IRS assisted system has been under investigation in the following research stages. The use of multiple IRS has been explored to further enhance system reliability and coverage by having multiple IRS panels working together to improve signal propagation [1],[4]. Optimal IRS selection methods have also been studied that can determine the optimum reflecting surface to achieve the maximum performance of the system, especially when multiple IRSs are used [2],[3]. Moreover, spectral efficiency maximization via weighted sum-rate and resource allocation have been explored to enhance the spectral efficiency of the IRS enhanced network [8].

Practical implementation issues such as modeling of the phase shift, channel estimation and design for low-energy IRS have been discussed in several studies. Minimizing the gap between theoretical models and real deployments has been studied by incorporating realistic phase shift constraints and optimising the beamforming [9]. The IRS-assisted channel estimation techniques have also been proposed for accurate configuration of the reflecting elements [10]. In addition, distributed IRS architectures have been studied for better energy efficiency and scalability in large-scale wireless networks [6].Although these developments have taken place, most of the current research has been conducted under the assumption of the static or quasi-static channel condition, in which the time variation in channel is sufficient to be ignored. In real 6G applications like high-speed mobile communications in vehicles and intelligent transportation systems (ITS) however, user mobility causes Doppler effects that lead to time-varying channels. This results in phase misalignment and considerable loss of performance when using conventional static IRS configuration. The current techniques implemented by IRS are then not directly applicable in a high-mobility environment.

To address this research gap,this work which introduces a mobility-aware dynamic IRS selection and phase adaptation scheme to take into consideration Doppler-induced channel variation. The proposed approach can adapt IRS operations with updated configurations based on time-varying channel conditions, thus leading to the constructive signal combining even at high-speed mobility. In this way, it offers higher reliability and spectral efficiency than traditional static IRS and non-IRS systems, which is good for future 6G high-mobility applications.

III. SYSTEM MODEL

In the considered system, a single user equipment (UE) is deployed in a high-mobility wireless environment, with the help of a base station (BS), multiple Intelligent Reflecting Surface (IRS) panels are deployed [4]. The IRS panels can be installed between the BS and UE to boost signal propagation and a reliable communication link, especially when the direct communication path suffers from high attenuation or blockage.A large number of passive reflecting elements are deployed within the IRS, and the BS is equipped with several antennas. Such reflecting elements can intelligently alter the phase of the incident electromagnetic wave for the purpose of enhancing the signal quality at the receiver.The communication system works in the millimeter-wave (mmWave) frequency band at 28 GHz which is very promising for the future 6G networks due to its availability of large bandwidth. But mmWave communication is very sensitive to path loss [14],[17], blockage and channel variations due to user mobility. Hence, IRS aided communication is regarded as an improve spectral efficiency and reliability of the wireless signal.

The wireless links between the BS and IRS, and between the IRS and UE are assumed to be Rician fading channels with both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components. The received signal at the user is given by

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$$y = \left(h_d + \sum_{n=1}^{N} h_{b,n}\, e^{j\theta_n} h_{u,n}\right)x + w \tag{1}$$

where:

- h_d represents the direct communication channel between the BS and UE,
- $h_{b,n}$ denotes the BS-to-IRS channel coefficient,
- $h_{u,n}$ denotes the IRS-to-UE channel coefficient,
- θ_n represents the phase shift applied at the nnn-th IRS element,
- x is the transmitted signal, and
- w denotes additive white Gaussian noise.

The Doppler effect due to user motion is added to the channel model for analyzing the mobility impact. The Doppler frequency is:

$$f_d = \frac{v}{\lambda} \tag{2}$$

Here, we use v to indicate the user velocity and λ to indicate the carrier wavelength. To cope with the Doppler effect, the wireless channel is time-varying and continuous phase variations and signal degradation are inevitable under high speed mobility.The system performance is measured using different Signal to Noise Ratio (SNR) values and user velocity at different values with the major performance parameter being the Bit Error Rate (BER) and achievable rate.

IV. PROPOSED DYNAMIC IRS SELECTION METHOD

Typical communication methods that require assistance from the IRS are assumed to have a static or slowly varying wireless channel. In a high-mobility scenario, e.g., in high-speed vehicular communications or intelligent transportation systems, due to the Doppler effect, the channel variations are very fast, resulting in misalignment of the signals and poor performance. To solve this problem, an IRS selection and phase adaptation scheme based on mobility information is proposed.The proposed technique models the effective channel gain reduction due to Doppler effect as a velocity-dependent scaling factor. First, several IRS panels are set up in the communication environment and in the transmission, the pilot signals are employed to estimate the channel condition [10] from BS to IRS and the UE. The dynamic IRS scheme applies a Doppler compensation factor to mitigate performance degradation. A velocity dependent attenuation factor is used to model the Doppler affected wireless channel.

$$h(t) = h e^{j2\pi f_d t} \tag{3}$$

With increasing user velocity, fast phase variations happen, which cause less signal alignment in the conventional static IRS system [2]. The suggested framework addresses this problem by incorporating a Doppler-aware scaling factor that reduces the impact of mobility on the reflected signal path.

Three different communication scenarios are tested to check the performance of the proposed method:

· Communication without IRS assistance

· Communication using static IRS

· Communication using the proposed dynamic IRS framework

Bit Error Rate (BER) and the achievable rate are used to evaluate the system performance. The BPSK modulation BER represented as

$$BER = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{1+\gamma}}\right) \tag{4}$$

where γ represents the instantaneous Signal-to-Noise Ratio (SNR).

The achievable rate of the system is computed using Shannon’s capacity formula:

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$$R = \log_2(1 + \gamma) \quad (5)$$

Through simulation, it is demonstrated that the proposed dynamic IRS framework enables the BER to be reduced and the achievable rate to be improved compared to the static IRS and non-IRS systems, especially when the mobility speed is high. The proposed approach is able to adapt to channel variations continually and significantly enhance communication reliability [16] and spectral efficiency in future 6G wireless networks.

The system is simulated in MATLAB under the following conditions:

- Carrier frequency: 28 GHz
- IRS elements: 64
- Velocity range: 0–300 km/h
- SNR range: 0–30 dB

V. RESULTS AND DISCUSSION

In this section Monte Carlo simulations are used to assess the performance of the proposed mobility-aware dynamic IRS structure in various scenarios of Signal-to-Noise Ratio (SNR) and user mobility. The simulations are performed with a carrier frequency of 28 GHz and N=64 IRS reflecting elements. The Bit Error Rate (BER) and achievable rate are used as the main metrics to compare the performance of the proposed dynamic IRS scheme with conventional static IRS and non-IRS communication systems.

Fig.1 shows the BER of three different communication scenarios (communication without IRS, communication with static IRS and communication with proposed dynamic IRS) at a user velocity of 250 km/h as a function of SNR.At low SNR, all the communication schemes have a relatively high BER, because noise is dominating the received signal. As SNR increases the BER slowly decreases for all cases, but it decreases faster for static IRS and non-IRS systems. The non-IRS scheme is the poorest performing, as there is no communication between the three schemes other than direct transmission, which suffers from high fading and mobility induced degradation.

The effective channel gain is increased in the case of IRS scheme, which results in improved BER performance as compared to the non-IRS case. However, the reflected signals start to drift away from the imposed IRS phase shifts as the mobility increases, because of the channel variations caused by Doppler effect. This means that at higher user velocities the BER reduction possible with the static IRS is reduced.The proposed dynamic IRS, on the other hand, results in the minimum BER throughout the SNR range. The proposed approach applies a Doppler compensation factor as a function of the current channel condition, ensuring constructive signal combining even when there are fast channel fluctuations. This kind of adaptation gives a substantial boost in the received signal quality and minimizes transmission errors.The improvement in the proposed dynamic IRS scheme over the conventional approaches increases with the increase of SNR values. The adaptive IRS approach is able to appropriately compensate for Doppler-induced phase variations, thereby improving the communication reliability in high-mobility environments. The results show that the proposed mobility-aware IRS mechanism is very effective in enhancing the communication reliability for future 6G wireless systems.

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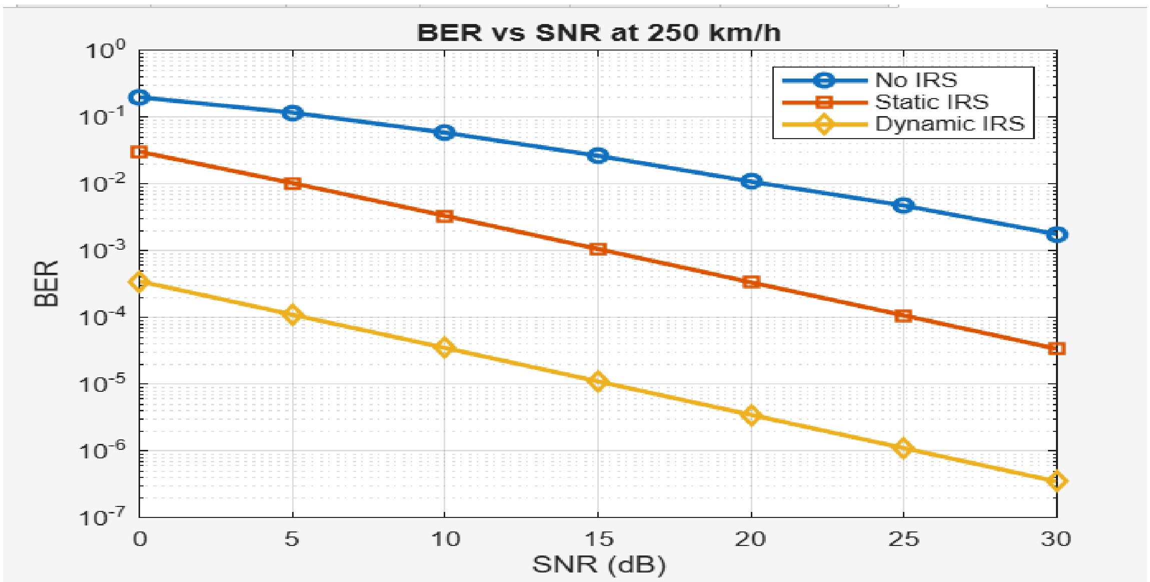

Fig.1: BER Vs SNR at velocity 250Km/h

Fig.2 shows the achievable rate performance of these three communication schemes as a function of velocity of the user at SNR = 20 dB. The achievable rate is the possible data transmission rate of the communication system under various mobility scenarios.However, the non-IRS system has the lowest possible rate under all velocity conditions, since the communication is totally dependent on the direct channel, which is severely affected by fading and path loss. There is no intelligent reflection mechanism to improve the quality of the channel, and the overall channel quality is still low.The IRS is a static system which provides a higher achievable rate than the non-IRS case, because of the extra reflected signal path formed by the IRS. As the velocity of the users increases, however, the rate that can be obtained gradually decreases. This degradation is due to the fact that the static IRS configuration can't cope with an occasional change in the channel, due to the Doppler effect. Thus, an alignment of the reflected and direct signal components is present, which lowers the received signal strength.

The proposed dynamic IRS mechanism always yields the maximum possible velocity rate at all speeds. The proposed method applies Doppler-aware compensation to reduce mobility-induced degradation and improve reflected signal alignment, thereby ensuring good signal alignment at high user speeds. This allows the system to maintain a high effective effective channel gain in the presence of Doppler-induced fading.The achievable rate is slightly reduced with the increase in velocity, but the performance degradation in the proposed scheme is considerably lower than that of the static IRS system. The proposed framework allows for the stable and reliable communication performance even at the velocities up to 250 km/h and the performance comparison of IRS schemes is given in table 1. This finding is consistent with the fact that dynamic IRS adaptation is highly beneficial for the mobile wireless communication environment that is anticipated in the future 6G networks.

Table 1 : Performance Comparison of Different IRS Schemes

Metric	**No IRS**	**Static IRS**	**Dynamic IRS**
BER Performance	Poor	Better	Best
Achievable Rate	Low	Moderate	High
Doppler Resistance	Low	Moderate	High
Signal Reliability	Weak	Improved	Strong
Performance at High Mobility	Poor	Degrades	Stable

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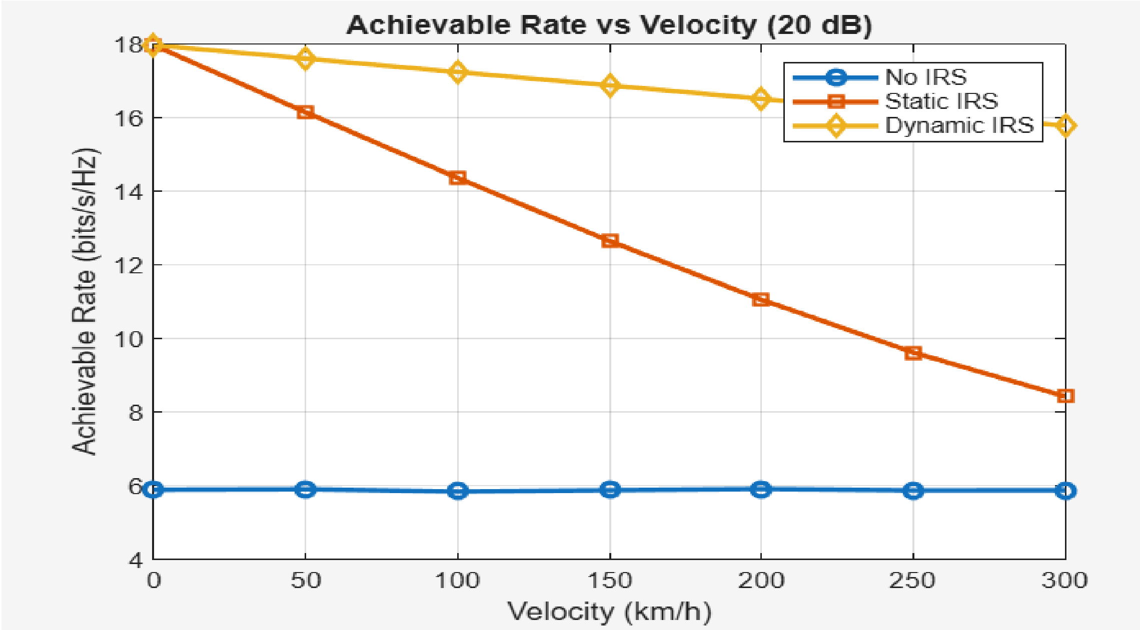

Fig.2: Achievable rate Vs Velocity at 20dB

Key Observations

The simulation results clearly show that the use of mobility-aware dynamic IRS adaptation in high-speed wireless communication systems is highly beneficial. The proposed framework is an effective solution to the Doppler-induced channel variations by using a Doppler-aware scaling approach according to the instantaneous channel.

Compared to conventional IRS system,the proposed method can provide following:

- Reduced Bit Error Rate (BER)
- Higher achievable rate
- Improved signal reliability
- Greater resistance to degradation of performance due to mobility

The results also demonstrate that static IRS configurations are not adequate for enabling reliable communication in high-mobility scenarios due to the fact that the fixed phase shifts are not capable of guaranteeing proper signal alignment when the channel conditions are rapidly changing.Overall, the proposed dynamic IRS framework is a practical and efficient solution to achieve reliable and high-capacity communication for future 6G wireless networks, especially for the applications concerning high-speed vehicular communication and intelligent transportation systems.

VI. CONCLUSION

In this paper, a mobility-aware intelligent reflecting surface (IRS)-assisted wireless communication framework in high-speed 6G network scenarios has been proposed which is different from conventional IRS systems, which are designed with the assumption of fixed channels, since it takes into account Doppler-induced time-varying channel effects to overcome the problems resulting from user mobility. A Doppler-aware IRS adaptation mechanism was introduced to overcome this effect by using a velocity-based compensation factor with regards to the instantaneous channel conditions, so as to ensure constructive signal combining even in the event of a rapid channel variation.

Monte Carlo simulation was used to measure the performance of the proposed framework with the key performance metrics being the Bit Error Rate (BER) and achievable rate. The results have shown that the proposed dynamic IRS scheme results in a significant improvement over the static IRS and non-IRS communication systems. The proposed method showed lower BER and higher achievable rate under high-speed mobility conditions, which demonstrated its effectiveness in alleviating the effect of Doppler-induced signal degradation.The simulation results also revealed that for such high-mobility environments, the conventional static IRS configurations are not adequate for ensuring reliable

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communication because of the phase misalignment resulting from the rapidly varying wireless channel. On the other hand the proposed dynamic IRS system could handle the fluctuations in channel and still have a low communication error rate even when the user velocity was as high as 250 km/h.

In conclusion, the proposed mobility-aware IRS framework offers a promising and practical approach to improve the communication reliability and spectral efficiency in future 6G wireless networks. The paper emphasizes the need for dynamic IRS adaptation in order to enable new high-speed applications that are emerging, e.g. intelligent transportation systems and high-speed vehicular communication. Moving forward, this framework can be expanded with machine learning optimization of the IRS, multiple communication scenarios between users, and realizing this system on hardware for real-world 6G networks.

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