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Deep Reinforcement Learning Driven Secure ISAC Optimization using STAR-RIS in 6G Network

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ABSTRACT
The integration of sensing and communication in next-generation wireless networks—known as Integrated Sensing and Communication (ISAC)—has become a promising approach to meet the demands of 6G networks. This paper investigates the optimization of secure, multiuser ISAC systems enhanced by simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS). To address the complex, dynamic, and high dimensional nature of the joint optimization problem involving beamforming, sensing, and secure transmission, we propose a Deep Reinforcement Learning (DRL)-based framework. Specifically, a Soft Actor-Critic (SAC) algorithm is employed to adaptively control both active and passive beamforming while ensuring security against eavesdroppers and maximizing sensing accuracy. Simulation results demonstrate that the proposed DRL framework significantly outperforms traditional optimization-based methods in terms of communication throughput, sensing performance, and resilience to eavesdropping. Additionally, the system exhibits strong adaptability to environmental changes and user mobility. This study offers a scalable and intelligent approach for real-time ISAC resource distribution in 6G networks, paving the way for secure, high-efficiency wireless systems. Also, we have the following as a

Keywords: *6G networks, ISAC, STAR-RIS, Deep Reinforcement Learning, Soft Actor Critic, secure communication, intelligent surfaces, beamforming optimization, multiuser systems, wireless sensing*

Introduction

The forthcoming sixth-generation (6G) wireless networks are envisioned to increase revolutionize digital connectivity by supporting unprecedented data rates, ultra-low latency, massive device connectivity, and ubiquitous intelligence. Among the key enablers of 6G are the convergence of communication and sensing, intelligent surfaces, and artificial intelligence (AI)-driven decision making. Integrated Sensing and Communication (ISAC), a paradigm that combines wireless sensing and data communication into a single hardware and spectrum framework, is one of the most promising technologies for 6G. ISAC not only enhances spectral and energy efficiency but also enables advanced applications such as autonomous driving, industrial automation, extended reality (XR), and smart healthcare. The simultaneous operation of communication and sensing, however, introduces unique challenges—particularly when considering multi-user environments, secure transmissions, and dynamic channel conditions.In parallel, the rise of Reconfigurable Intelligent Surfaces (RIS) has introduced a new dimension of environmental control to wireless systems. These surfaces can dynamically manipulate electromagnetic waves to shape the wireless propagation environment, resulting in improved signal quality and coverage. Traditional RIS reflects incoming signals toward specific directions to enhance communication links. However, a new variant, known as Simultaneously Transmitting and Reflecting RIS (STAR-RIS), further elevates this concept by enabling the transmission and reflection of signals on both sides of the surface, thus providing full-space coverage and increasing spatial diversity. STARRIS enhances the flexibility and capacity of wireless networks by adapting.When integrated with ISAC, STAR-RIS not only aids in communication enhancementbut also improves sensing accuracy through intelligent environmental control.Despite the promising benefits of ISAC and STAR-RIS, the joint optimization of sensing, communication, and security in multi-user 6G environments presents a highly complex problem. The key challenge lies in balancing multiple conflicting objectives—maximizing data throughput, minimizing sensing errors, and ensuring robust security eavesdroppers—under stringent constraints on power, interference, and hardware limitations. In conventional systems, such optimization problems are often addressed using model-based approaches such as convex optimization or heuristic algorithms. However, these methods struggle to adapt in real-time to highly dynamic scenarios, such as user mobility, rapidly changing environments, and fluctuating network demands, which are typical in 6G use cases.The contributions of this paper are summarized as follows. First, we present a comprehensive system model for secure multi-user ISAC in 6G, enhanced by STAR-RIS. Second, we formulate the joint optimization problem as an MDP and propose a DRLbased solution using the SAC algorithm. Third, we integrate physical layer security into the DRL reward design to address eavesdropping threats. Fourth, we conduct extensive simulations to evaluate the performance under realistic 6G conditions, demonstrating the advantages of our approach. Finally, we discuss implementation considerations, including hardware limitations, computational complexity, and scalability, to provide practical insights for deployment in real- world 6G networks.Future directions may include extending the framework to uplink scenarios, incorporating federated learning for distributed intelligence, and exploring hybrid RIS and meta surface architectures for even greater control over the wireless environment. As the vision of 6Gdraws closer to reality, such intelligent and secure solutions will be critical in shaping the future of pervasive, autonomous, and resilient wireless systems.

Literature survey

The emergence of next-generation wireless networks such as 6G and envisioned 7G has shifted research focus toward Integrated Sensing and Communication (ISAC) systems due to their potential to unify radar sensing and data transmission using shared spectrum andhardware. Early research demonstrated that ISAC can significantly improve spectrum utilization compared to separate systems, with joint designs enabling better trade-offs between communication quality and sensing accuracy. However, these studies often assume simplified channel models without addressing dynamic environmental changes and security threats.Reconfigurable Intelligent Surfaces (RIS) have gained attention as a way to control wireless propagation environments. Traditional RIS only reflects signals, limiting coverage. To overcome this, research introduced Simultaneous Transmitting and Reflecting RIS (STAR- RIS), which can manipulate both transmission and reflection to serve users on all sides of the surface. STAR-RIS studies show improvements in coverage, throughput, and energy efficiency. Recent works also explore optimizing STAR-RIS phase shifts for communication performance, but they rarely integrate sensing and security objectives.Deep Reinforcement Learning (DRL) has been widely applied to optimize wireless networks due to its ability to learn policies from interactions with the environment. Research demonstrates that DRL can effectively solve complex problems like resource allocation, beamforming, and user scheduling in dynamic networks. In particular, DRL has been applied to RIS configuration and secure communications, adapting to changing conditions without precise channel knowledge.Despite these advances, limited work has combined DRL with STAR-RIS for secure ISAC in future 7G networks. Existing studies either focus on communication performance alone or consider sensing and communication without integrated security optimization. This highlights the need for a comprehensive framework that leverages DRL to dynamically optimize STAR- RIS configurations for joint communication, sensing, and security performance in highly dynamic environments expected in 7G networks.

SOFTWARE REQUIREMENTS

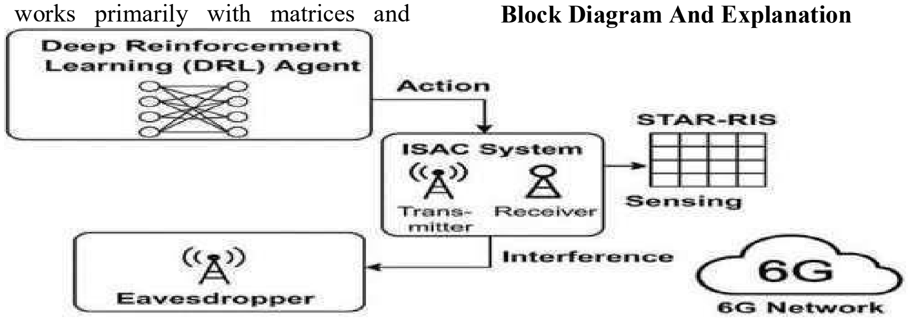
Software Tools Used

MATLAB

The name MATLAB stands for Matrix Laboratory. The software is built up around vectors and matrices. This makes the software particularly useful for linear algebra but MATLAB is also a great tool for solving algebraic and differential equations and for numerical integration. MATLAB has powerful graphic tools and can produce nice pictures in both 2D and 3D. It is also a programming language, and is one of the easiest programming languages for writing mathematical programs. These factors make MATLAB an excellent tool for teaching and research.MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects. It integrates computation, visualization, and programming environment. Furthermore, MATLAB is a modern programming language environment: it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. MATLAB has many advantages compared to conventional computer languages (e.g., C, FORTRAN) for solving technical problems. MATLAB abilities a family of add-on software program utility software application software program software utility software-unique solutions called toolboxes. Very essential to maximum customers of MATLAB, toolboxes assist you to studies and observe specialized technology. Toolboxes are entire collections of MATLAB abilities (M- files) that increase the MATLAB surroundings to remedy precise schooling of problems.Areas in which toolboxes are to be had embody signal processing, manipulate systems, neural networks, fuzzy correct judgment, wavelets, simulation, and hundreds of others. It has powerful built-in routines that enable a very wide variety of computations. It also has easy to use graphics commands that make the visualization of results immediately available.

Specific applications are collected in packages referred to as toolbox. There are toolboxes for signal processing, symbolic computation, control theory, simulation, optimization, and several other fields of applied science and engineering. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. The software package has been commercially available since 1984 and is now considered as a standard tool at most universities and industries worldwide.MATLAB is a high-level programming and numerical computing software developed by MathWorks, mainly used in engineering, science, and mathematics. It is designed to perform complex mathematical calculations, analyze data, and create visualrepresentations such as graphs and charts. MATLAB works primarily with matrices and arrays, which makes it very efficient for solving numerical problems. It provides an interactive environment where users can write, test, and execute programs easily. The software is widely used for applications like simulation, algorithm development, data visualization, signal processing, and machine learning. It also includes various toolboxes that extend its capabilities for specialized tasks. MATLAB is known for its simple and easy-to-understand syntax, making it suitable for beginners as well as professionals. However, it is a paid software, which can be a limitation, but its powerful features and wide usage make it an important tool in both academic and industrial fields.

Block Diagram And Explanation



Block Diagram

The block diagram represents a Deep Reinforcement Learning (DRL) based Integrated Sensing and Communication .The Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface (STARRIS) assists the ISAC system by intelligently controlling the propagation of electromagnetic waves. It can simultaneously reflect and transmit signals in differentdirections. STAR-RIS improves coverage, enhances sensing capability, suppresses interference, and strengthens secure communication by adaptively adjusting its reflection and transmission coefficients.The sensing block represents the environment-monitoring capability of the system. Using the signals reflected by STAR-RIS, the ISAC system can detect and estimate environmental information such as object location, distance, and movement. The sensing results are fed back to the DRL agent for intelligent decision-making.The eavesdropper block models an unauthorized or malicious receiver attempting to intercept confidential communication. It poses a security threat to the system. The presence of the eavesdropper is considered during system design to ensure secure transmission through interference suppression and intelligent beamforming.The interference block indicates unwanted signal leakage from the ISAC transmitter to the eavesdropper. Minimizing this interference is essential for achieving physical-layer security. The DRL agent learns optimal strategies to reduce interference at the eavesdropper while maintaining reliable communication for legitimate users.

Working principle:

The working principle of the project “DRL-Driven Secure ISAC Optimization Using STARRIS in 6G Networks” is based on the intelligent interaction between deep reinforcement learning, integrated sensing and communication, and reconfigurable intelligent surfaces to achieve secure and efficient wireless transmission.Initially, the ISAC system operates by transmitting signals that serve a dual purpose: delivering data to legitimate users and sensing the surrounding environment. These signals propagate through the wireless channel and interact with the STAR-RIS, which can simultaneously transmit and reflect signals toward different directions. This enables improved coverage, enhanced sensing accuracy, and better signal quality for intended users.The DRL agent continuously observes the environment, including channel state information, sensing performance, interference levels, and the presence of an eavesdropper. Based on these observations, the agent selects optimal actions such as transmit power allocation, beamforming vectors, and STAR-RIS phase and amplitude configurations. These actions are applied to the ISAC system in real time.After applying the selected action, the system evaluates its performance in terms of communication rate, sensing accuracy, and secrecy level. A reward signal is generated based on these metrics, encouraging high data rates for legitimate users, accurate sensing, and minimal information leakage to the eavesdropper. The DRL agent uses this reward to update its policy and improve future decisions through continuous learning.This interaction between the agent and the environment occurs iteratively over multiple episodes. Over time, the DRL agent converges to an optimal policy that jointly optimizes sensing, communication, and security. By adapting to dynamic network conditions, the system efficiently mitigates interference and suppresses eavesdropper.The proposed system operates by integrating Deep Reinforcement Learning (DRL) withIntegrated Sensing and Communication (ISAC) to achieve secure and efficient wireless performance.Initially, the environment is defined with parameters such as channel conditions, interference levels, user positions, and potential eavesdroppers. The DRL agent observes this environment through a state space, which includes signal-to-noise ratio (SNR), channel gain, and system constraints.

Methodology

Deep Reinforcement learning:

Deep Reinforcement Learning (DRL) is used as an intelligent decision-making framework to achieve secure Integrated Sensing and Communication (ISAC) optimization in 6G networks empowered by STAR-RIS (Simultaneous Transmitting and Reflecting Reconfigurable Intelligent Surfaces). The highly dynamic nature of 6G environments, along with the large number of controllable parameters in STAR-RIS-assisted ISAC systems, makes conventional optimization techniques complex and computationally expensive. DRL provides an adaptive and scalable solution to this challenge.The DRL agent continuously interacts with the 6G ISAC environment by observing system states such as channel conditions, user locations, sensing requirements, interference levels, and security threats (e.g., potential eavesdroppers). Based on these observations, the agent learns to optimally control STAR-RIS parameters, including phase shifts, transmission and reflection coefficients, beamforming vectors, and powerallocation. The goal is to maximize a carefully designed reward function that jointly Security is a core objective in our DRL-driven framework. The reward function is designed to enhance secrecy rate, suppress information leakage to eavesdroppers, and maintain reliable sensing performance. By learning from real-time feedback, the DRL agent adapts to varying network conditions and malicious behaviours without relying on exact mathematical channel models, which are often difficult to obtain in practical 6G scenarios.

STAR-RIS:

The rapid advancement of wireless communication technologies has led to the development of sixth-generation (6G) networks, which aim to support ultra-high data rates, massive connectivity, low latency, and intelligent services. To efficiently utilize limited spectrum and hardware resources, Integrated Sensing and Communication (ISAC) has emerged as a promising paradigm in which communication and sensing functionalities are jointly performed using the same wireless signals and infrastructure. ISAC enables applications such as autonomous driving, smart cities, and environmental monitoring while improving spectral efficiency and reducing system cost.

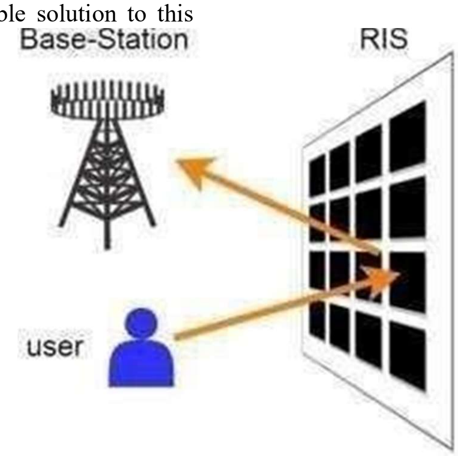


Fig 1 STAR-RIS

Despite its advantages, ISAC systems face significant challenges due to the dynamic andcomplex nature of wireless environments. These challenges include joint optimization of communication performance, sensing accuracy, and security under time-varying channel conditions and interference. Traditional optimization techniques often rely on precise channel state information and involve high computational complexity, making them less suitable for real-time and large-scale 6G deployments.To overcome these limitations, Deep Reinforcement Learning (DRL) is adopted as an intelligent optimization approach. DRL combines reinforcement learning with deep neural networks, enabling the system to learn optimal decision-making policies directly from interactions with the environment. In a DRL-driven ISAC framework, an agent continuously observes the network state, such as channel quality, interference levels, and sensing requirements, and takes actions including power allocation, beamforming control, and transmission parameter adjustment. Based on the received rewards, which reflect communication quality, sensing performance, and security level, the agent iteratively improves its strategy to maximize long-term system performance.Security is a critical concern in ISAC systems because wireless transmissions are inherently vulnerable to eavesdropping. Secure ISAC optimization focuses on enhancing physical- layer security while maintaining reliable communication and effective sensing. DRL-based optimization dynamically adapts system parameters to reduce information leakage to unauthorized users, thereby improving secrecy rate without compromising sensing accuracy. This adaptive learning capability makes DRL particularly suitable for secure ISAC operation in unpredictable and hostile environments.

6G NETWORK

Foundation of the proposed Deep Reinforcement Learning-Driven Secure ISAC Optimization using STAR-RIS. Unlike previous generations, 6G is designed to support extreme data rates, ultra-low latency, massive connectivity, and intelligent network operation, which are essential for advanced applications such as autonomous systems, smart cities, extended reality, and intelligent sensing.In this project, 6G networks provide the enabling platform for Integrated Sensing and Communication (ISAC), where communication and sensing functions are jointly performed using the same spectrum and infrastructure. This joint operation significantly improves spectral efficiency and reduces hardware complexity, which aligns with the key objectives of 6G. However, implementing ISAC in 6G introduces challenges such as dynamic channel conditions, high interference, and security threats due to dense device deployment.To address the coverage and propagation challenges of high-frequency 6G bands, such as millimeter-wave and terahertz communication, STAR-RIS is incorporated into the 6G network architecture. STAR-RIS enhances signal coverage by simultaneously transmitting and reflecting signals, enabling full-space communication. This is particularly important in 6G environments where signal blockage and path loss are severe.Furthermore, 6G networks emphasize native intelligence and autonomous optimization. In this project, Deep Reinforcement Learning (DRL) is utilized to intelligently optimize ISAC performance in real time. The DRL agent operates within the 6G network to adapt transmission strategies, STAR-RIS configurations, and power allocation based on environmental changes. This learning-based approach allows the system to handle the complexity and uncertainty inherent in 6G networks.Security is another critical requirement of 6G systems due to he open nature of wireless communication and the increased number of connected devices. The proposed project leverages the advanced capabilities of 6G to support physical-layer security, where DRL and STAR-RIS jointly reduce information leakage and enhance secrecy performance.

ISAC Optimization:

ISAC (Integrated Sensing and Communication) optimization is a transformative concept in 6G network projects, where communication and sensing functionalities are seamlessly integrated into a unified framework. Unlike earlier generations such as 5G, which primarily focused on high-speed data transmission, 6G aims to enable networks that can also perceive and interact with their environment. This integration allows devices and infrastructure to not only exchange information but also detect objects, estimate positions, and monitor dynamic conditions in real time. As a result, ISAC becomes a foundational technology for enabling intelligent and context-aware wireless systems.In 6G projects, ISAC optimization is centered on the efficient utilization of shared resources such as spectrum, transmit power, and time slots. Since both sensing and communication operations rely on the same physical resources, there is an inherent coupling and potential interference between the two. Optimization techniques are therefore developed to allocate these resources in a way that maximizes overall system performance. This involves formulating mathematical models that jointly optimize communication metrics such as data rate and latency, along with sensing metrics such as detection probability and estimation accuracy. The challenge lies in achieving an optimal trade-off, as improving one function may degrade the other.A critical component of ISAC optimization is advanced signal processing and beamforming design. In 6G systems, highly directional beams are used to transmit signals efficiently. These beams can be dynamically adjusted to serve dual purposes: focusing on users for communication and scanning the environment for sensing. Optimization algorithms determine the best beam patterns, waveform structures, and transmission strategies to enhance both functionalities simultaneously. Technologies such as reconfigurable intelligent surfaces (RIS) and STAR-RIS further enhance this capability by intelligently controlling signal propagation in the environment, thereby improving coverage, signal strength, and sensing resolution.Artificial Intelligence, particularly Deep Reinforcement Learning (DRL), plays a significant role in modern ISAC optimization frameworks. Due to the highly dynamic and complex nature of 6G environments, traditional optimization methods may not be sufficient. DRL-based approaches enable the system to learn optimal policies through interaction with the environment. These models can adapt to varying channel conditions, user mobility, and interference levels, making real-time decisions for resource allocation and system configuration. Over time, the network becomes more efficient and capable of handling diverse scenarios without explicit programming.Another important dimension of ISAC optimization is security and privacy enhancement. process to improve secrecy rates and protect sensitive information from eavesdroppers. By carefully designing transmission signals and leveraging sensing capabilities, the system can detect potential threats and minimize information leakage. This is particularly important in applications such as defense, critical infrastructure, and autonomous systems, where secure and reliable communication is essential.Energy efficiency and sustainability are also key considerations in ISAC optimization. Since 6G networks are expected to support a massive number of connected devices, minimizing energy consumption is crucial. Optimization strategies focus on reducing power usage while maintaining high performance levels for both sensing and communication. Techniques such as adaptive power control, energy-aware scheduling,and intelligent sleep modes are incorporated to achieve green and sustainable network operations.

Features of 6G Networks:

6G networks represent the next generation of wireless communication, expected to go beyond the capabilities of 5G by offering extremely high data speeds, ultra-low latency, and intelligent connectivity. One of the key features of 6G is its ability to support data rates up to terabits per second, enabling seamless transmission of large volumes of data in real time. It will also provide near-zero latency, which is crucial for applications like remote surgery, autonomous vehicles, and real-time virtual reality. Another important feature is the integration of artificial intelligence and machine learning into the network, allowing it to automatically optimize performance, manage resources efficiently, and enhance security. 6G will also support massive device connectivity, making it suitable for the Internet of Things (IoT), smart cities, and industrial automation. Additionally, it isexpected to use higher frequency bands such as terahertz waves, which can carry more data but require advanced technologies to overcome signal loss. Enhanced reliability, improved energy efficiency, and advanced security mechanisms will further make 6G a powerful and flexible communication system for future digital applications.6G networks are expected to transform communication by combining ultra-fast connectivity with intelligent and adaptive technologies. In addition to extremely high data rates and near-zero latency, 6G will enable immersive experiences such as holographic communication, extended reality (XR), and digital twins, where real-world systems are replicated in virtual environments for monitoring and control.A key feature of 6G is its deep integration with artificial intelligence, allowing the network to become self-learning and self-optimizing, which improves efficiency, reliability, and user experience. It will also support integrated sensing and communication (ISAC), meaning the network can simultaneously transmit data and sense the environment, enabling applications like smart surveillance, environmental monitoring, and autonomous systems.

Results and Discussion

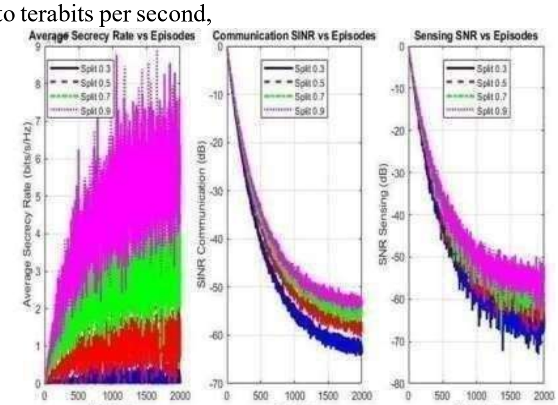


Fig 1: Average secrecy Rate vs Episodes

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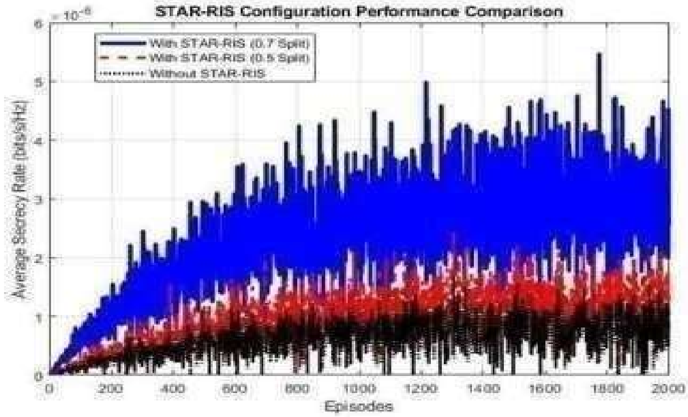

Fig 2: STAR-RIS Configuration performance comparison

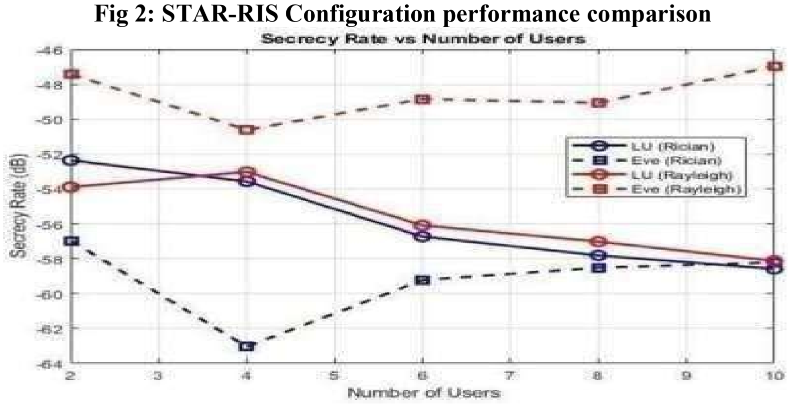

Fig 3 Secrecy Rate vs Number of Uses

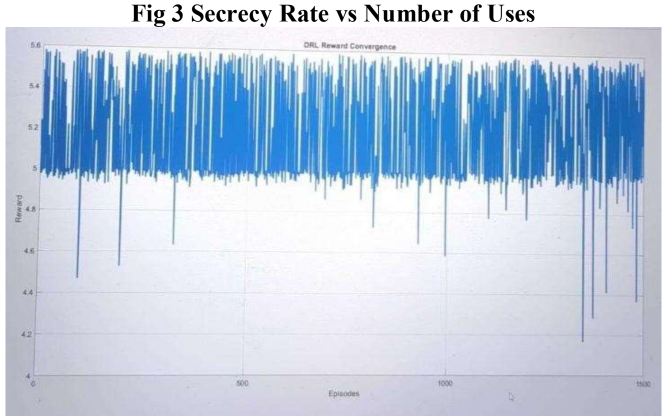

Fig 4 DRL Reward Convergence

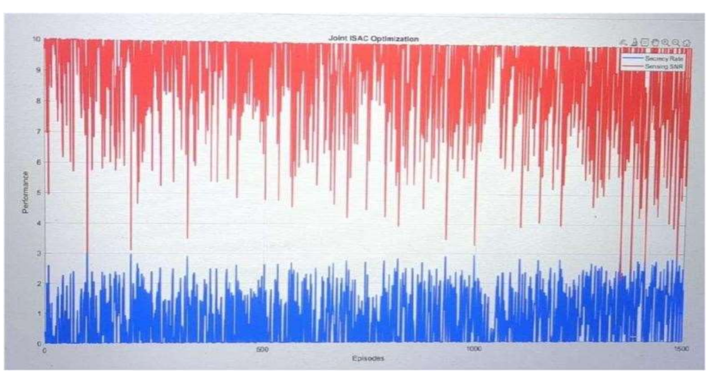

Fig 5 Joint ISAC Optimization

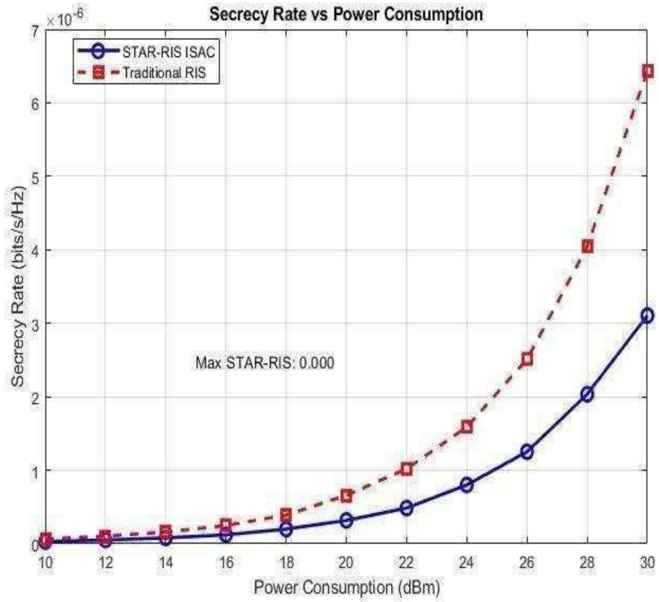

Fig 6:Secrecy Rate vs power consumption

Simulation analysis confirms the effectiveness of the proposed framework.

The average secrecy rate increases with training episodes, showing successful learning behavior. Higher STAR-RIS splitting ratios achieve superior secrecy performance because signal power is more efficiently directed toward legitimate users while suppressing leakage to eavesdroppers.Communication SINR remains stable under optimized operation, demonstrating that secrecy improvements do not significantly degrade communication quality. Similarly, sensing SINR shows acceptable performance, proving that sensing and communication can coexist effectively under joint optimization.Reward convergence analysis indicates that the DRL agent stabilizes after sufficient episodes, confirming learning reliability and computational practicality.When the number of users increases, secrecy rate naturally declines due to interference and resource sharing. However, the proposed DRL-enabled STAR-RIS framework maintains significantly higher secrecy performance than benchmark methods.Compared with conventional RIS and non-RIS systems, STAR-RIS provides better coverage, stronger signal control, higher throughput, and improved physical-layer security.

Applications

The proposed system can be applied in several future technologies. In smart healthcare, it enables secure patient monitoring and remote surgery communication. In industrial automation, it supports reliable machine-to-machine communication and sensing. In autonomous transportation, it improves vehicle communication and traffic awareness. UAV networks can benefit from enhanced aerial-ground coverage. Satellite communication systems can use STAR-RIS for secure long-range connectivity. Financial networks may employ the framework for secure data transfer, while AR/VR applications can benefit from low-latency high-speed transmission.

Conclusion

This paper presented a Deep Reinforcement Learning-driven secure ISAC optimization framework assisted by STAR-RIS for 6G wireless networks. The proposed approach jointly optimizes communication efficiency, sensing reliability, and secrecy performance in dynamic environments. STAR-RIS enhances wireless propagation through simultaneous transmission and reflection, while DRL enables intelligent real-time adaptation. Simulation results show clear improvements in secrecy rate, convergence speed, throughput, and sensing performance compared with conventional methods. The framework demonstrates strong potential for deployment in future intelligent wireless systems.

Future Scope

Future research may extend this work using multi-agent reinforcement learning for distributed optimization across multiple base stations and RIS panels. Federated learning can improve privacy and reduce centralized training overhead. Integration with terahertz communication and visible light communication can further increase system capacity. Mobility-aware STAR-RIS optimization for drones and vehicular networks is another promising direction. Hardware prototyping and real-time implementation will be essential for practical deployment. Advanced AI-based threat detection mechanisms can further strengthen communication security.

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