Security Analysis of Friendly Jamming Schemes for Ultra Reliable Low Latency Communications in 5G Networks

A Case Study Assessment

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Abstract

Ultra reliable low latency communications, or URLLC, are one of the most demanding service classes in 5G networks. They support applications such as autonomous driving, industrial control, and remote surgery, where even short communication failures can have serious consequences. Meeting very strict delay and reliability targets makes it difficult to rely only on traditional cryptography, which often introduces extra processing time and protocol overhead. Friendly jamming, a physical layer security technique in which trusted nodes transmit artificial noise to confuse eavesdroppers, offers an attractive alternative or complement.

This paper analyzes friendly jamming in URLLC through a case study style assessment. It focuses on three main vulnerability areas: challenges in obtaining accurate channel state information, self interference issues in full duplex systems, and resource allocation conflicts between security functions and performance goals. Several mitigation strategies are discussed, including artificial intelligence based adaptive jamming, the use of reconfigurable intelligent surfaces, hybrid frameworks that combine cryptography with physical layer security, and cooperative jamming with unmanned aerial vehicles.

The analysis shows that friendly jamming can significantly improve security in URLLC scenarios, but it is not a complete solution on its own. Practical deployment must account for latency budgets, energy and spectrum constraints, and the direction of future 6G developments.

Keywords: friendly jamming, URLLC, physical layer security, 5G networks, jamming based defense

Introduction

Background

Fifth generation mobile networks introduced three broad service categories: enhanced mobile broadband, massive machine type communications, and ultra reliable low latency communications. Among these, URLLC is the most demanding in terms of reliability and delay. The International Telecommunication Union specifies reliability above 99.999 percent and end to end latency below one millisecond for URLLC services (International Telecommunication Union, 2020). These requirements are motivated by use cases such as coordinated autonomous vehicles, closed loop industrial control, and remote medical procedures.

Wireless communication, however, is naturally exposed to eavesdropping and interference. Signals travel through open space and can be received by anyone with suitable equipment. Conventional security solutions rely heavily on cryptographic protocols that introduce extra computation and signaling, such as key exchange, authentication, and repeated encryption and decryption. For many URLLC devices, especially small sensors and embedded controllers, this extra load can be problematic. It can either exceed their processing capabilities or push end to end delay beyond what the application can tolerate.

Physical layer security aims to complement traditional methods by using properties of the wireless channel itself to protect confidentiality. Instead of only relying on mathematical hardness assumptions, it uses ideas such as secrecy capacity, artificial noise, and beamforming. Friendly jamming is a central tool in this area. In such schemes, trusted nodes purposely transmit interference that reduces the signal quality at potential eavesdroppers while keeping the signal to interference plus noise ratio acceptable at legitimate receivers.

Research Objectives

This paper uses a case study perspective to examine friendly jamming in URLLC environments, with four objectives:

1. To explain how friendly jamming schemes are intended to work in URLLC settings and where they fit in the overall security architecture.
2. To identify specific vulnerabilities and attack paths that may limit their effectiveness in practice.
3. To propose mitigation strategies that are technically realistic and consistent with URLLC timing and reliability requirements.
4. To discuss feasibility, including resource costs, compatibility with current 5G infrastructure, and expected developments on the road to 6G.

Case Study Focus

The discussion builds on recent work on friendly jamming for URLLC and related 5G and 6G scenarios, including device to device links, heterogeneous networks, unmanned aerial vehicle communication, and large scale internet of things deployments. These systems often combine friendly jamming with technologies such as beamforming, multiple input multiple output

transmission, full duplex radios, and relay based architectures. This wide variety of settings allows a richer vulnerability and mitigation analysis than a single narrow example.

Case Study Summary

Friendly Jamming for URLLC Security

Core Concepts

The basic idea behind friendly jamming is controlled interference. Alongside the legitimate transmitter and receiver, the system includes trusted nodes that act as jammers. These friendly jammers send artificial noise or structured interference. The goal is to reduce the eavesdropper channel capacity while preserving reliable communication for the intended receiver.

The security gain depends on the difference between the quality of the legitimate link and the eavesdropper link. If the system can ensure that the legitimate receiver always has a better effective channel than any eavesdropper, then it can achieve a positive secrecy capacity. The design questions then include where to place the jammers, how much power they should use, and how to shape their signals in time, frequency, and space.

Integration with Advanced Wireless Techniques

In modern networks, friendly jamming is rarely used in isolation. It is often combined with:

1. Beamforming, to direct both information signals and jamming signals more accurately, improving useful reception and reducing collateral interference.
2. Multiple antenna systems, which allow different antennas or antenna groups to carry information and noise in parallel.

3. Full duplex operation, where a node transmits and receives at the same time, potentially acting as both a data relay and a friendly jammer.

4. Relay and cooperative schemes, in which intermediate nodes both extend coverage and participate in jamming to protect multi hop communication.

These combinations can provide strong protection in theory but also increase the number of places where things can go wrong. More components and control loops mean more possible security and implementation weaknesses.

URLLC Application Contexts

URLLC applications are quite diverse, and this strongly affects friendly jamming design. A few examples are:

Autonomous vehicles need very fast and reliable message exchange for collision avoidance and coordination. The communication environment is highly dynamic due to mobility.

Industrial automation involves many sensors and actuators inside factories or plants. The environment can be harsh for radio propagation, with metal structures, reflections, and interference from other equipment. Reliability is critical since communication faults can halt production or damage equipment.

UAV networks operate in three dimensions and often under tight energy constraints. They may provide coverage, sensing, or both. Their changing altitude and position create different channel conditions than ground networks.

Remote medical applications, such as teleoperation in surgery, combine extremely strict reliability demands with privacy and integrity requirements. In these networks, both traditional data protection and physical layer protection are important.

Each of these domains imposes different priorities on latency, energy, coverage, and security strength, which shapes how friendly jamming can realistically be used.

Vulnerability Analysis

Channel State Information Acquisition

Description

Friendly jamming works best when the system has good knowledge of channel state information. For the legitimate link, this information is usually obtained using pilot signals and estimation algorithms. For URLLC, the short time budget limits how much pilot overhead the system can allocate. That can lead to inaccurate or outdated channel information, especially in fast changing environments.

The situation is worse with eavesdroppers. Passive eavesdroppers do not transmit pilots and may not be visible to the network at all. The transmitter and jammers then have to design signals under partial, statistical, or guessed information about the eavesdropper channel. This uncertainty makes it hard to guarantee secrecy capacity in practice.

Threat Scenarios

Several attack scenarios follow from this limitation. A passive eavesdropper with advanced antennas and signal processing can position itself at locations where the effect of friendly jamming is weakest. Since the system does not know its exact channel, the jamming may be optimized for the wrong region.

Pilot contamination is another possible attack. An active adversary sends fake pilot signals to mislead channel estimation. If friendly jamming relies on those estimates, it may direct noise in the wrong directions, accidentally helping the attacker.

Mobility also creates problems. For instance, in vehicle to everything communication, legitimate and illegitimate nodes move quickly. Channel information becomes stale very fast. Friendly jamming designed on old information may be ineffective or, in the worst case, may hurt the legitimate receiver more than the eavesdropper.

Impact

If attackers exploit these weaknesses, the consequences can be serious. In road traffic systems, successful eavesdropping could reveal vehicle trajectories and coordination messages. In industrial environments, it could expose production data or safety related control logic. In medical use cases, it could compromise patient privacy or allow manipulation of health data.

Because URLLC aims for extremely high reliability, security failures are more than a side issue. Loss of confidentiality can lead to actions that ultimately affect system safety and reliability as well.

Self Interference in Full Duplex Systems

Description

Full duplex communication lets a node transmit and receive on the same frequency at the same time. This is attractive for URLLC and friendly jamming, because it removes the need to separate jamming and data transmission in time or frequency. However, it also introduces strong self interference, since the transmitted signal is many orders of magnitude stronger than the received signal arriving at the same radio.

Self interference cancellation methods work in the analog domain, in the digital domain, or through antenna design. In practice, they cannot remove all interference. Remaining interference raises the effective noise floor and may significantly reduce the signal quality of the desired received signal. Hardware imperfections, amplifier nonlinearity, and phase noise make this problem worse.

Threat Scenarios

From a security viewpoint, attackers may try to exploit self interference and the algorithms that attempt to cancel it. For example:

An eavesdropper could use knowledge of the structure of the jamming signals to try to estimate and subtract them from its own received signal, especially if the same patterns are repeated over time.

An active attacker could inject signals that confuse the self interference cancellation algorithms, leading to poor cancellation and severe performance degradation for legitimate receivers.

Nonlinear distortion created in the transmitter chain can leak additional information about the transmitted signal. If cancellation focuses on the main linear component, the remaining nonlinear artifacts may still carry useful information for an eavesdropper.

Impact

If friendly jamming in a full duplex system is not carefully designed, it can unintentionally reduce the quality of service for legitimate users, or even open side channels for attackers. In URLLC contexts, any loss of reliability or increase in latency is problematic. At the same time, if residual interference is large enough, operators might disable or reduce jamming to preserve performance, which weakens security.

Resource Allocation Conflicts

Description

URLLC networks operate under tight constraints in power, bandwidth, computation, and energy. Friendly jamming consumes resources in all of these dimensions. Power used for jamming is not available for information transmission. Spectrum occupied by jamming cannot carry user data.

Computation is another issue, especially for advanced schemes that use machine learning or optimization to decide how to jam. These algorithms consume processing cycles and memory, and they add some decision making delay. If this overhead is too large, it may conflict with URLLC latency targets.

Threat Scenarios

Attackers can try to exploit the resource hungry nature of jamming in several ways. For instance:

They may trigger conditions in which the system repeatedly enters high power jamming modes, draining the batteries of energy constrained devices such as sensors or UAVs.

By causing the system to overestimate the threat level, attackers may push it into defensive modes that reserve too much power and spectrum for jamming. This can degrade service quality for legitimate users and amount to an indirect denial of service attack.

In systems with heavy AI based jamming control, adversaries may craft inputs that force the controller into worst case computation paths, thereby increasing decision delay and potentially violating latency requirements.

Impact

Resource related vulnerabilities threaten not only confidentiality but also availability. If friendly jamming causes excessive energy consumption or blocks too much usable spectrum, URLLC services may fail to meet their reliability targets. This is especially dangerous in mission critical settings where the application cannot tolerate dropped or delayed messages.

Proposed Mitigation Strategies

AI Based Adaptive Friendly Jamming

Technical Approach

Artificial intelligence and machine learning can help friendly jamming cope with uncertain or partial channel information. Instead of relying on exact channel state for each eavesdropper, the jammer can use reinforcement learning to adapt its behavior over time.

Actor critic methods are one promising approach. In such systems, an actor module chooses jamming actions, such as power levels, beam directions, or time slots, based on the current observed state of the network. A critic module estimates how good those actions are in terms of a reward function that reflects secrecy performance, interference to legitimate users, and resource usage (Dardari & Closas, 2024; Johnson & Smith, 2024).

The model learns by interacting with the environment, observing which actions lead to successful secure communication and which do not. Over time, it can discover robust policies that work well even with imperfect knowledge of the actual eavesdropper channels.

Mitigation Effect

This adaptive approach reduces reliance on perfect channel state information. The learning process can take into account patterns in acknowledgments, retransmissions, and signal quality measurements to infer where and how jamming is effective. It is especially useful in the presence of passive eavesdroppers, where direct channel estimation is impossible.

Moreover, adaptive jamming can respond to changes in mobility or environment more quickly than static schemes designed for fixed channel models. This is valuable in vehicular and UAV scenarios.

Practical Considerations

The main concerns are computational cost and training time. URLLC systems cannot afford very long learning phases during which security is weak. Pre training in realistic simulation environments, followed by fine tuning in the field, can ease this problem. Edge computing nodes can host the heavier models, with devices offloading decision making to nearby edge servers when possible.

Energy usage of continuous learning must also be controlled. In some cases, it may be better to use a trained model in inference mode only, and retrain or update it on larger time scales rather than continuously.

Reconfigurable Intelligent Surfaces

Technical Approach

Reconfigurable intelligent surfaces are programmable panels with many small reflecting elements. By setting the phase and amplitude of each element, they can shape how radio waves reflect in the environment (Chen et al., 2024).

For friendly jamming, RIS can be used to steer legitimate signals toward intended receivers and to create destructive interference in regions where eavesdroppers are likely to be located. Some parts of the surface can be dedicated to improving coverage and reliability, while others are tuned to create jamming effects.

Recent work shows that RIS can distinguish between receivers that are only a few millimeters apart, which allows very fine grained control over who gets a clean signal and who experiences heavy interference.

Mitigation Effect

RIS technology helps with all three vulnerability domains:

It relaxes the need for exact eavesdropper channel estimation, since it can create interference zones rather than aiming at specific points.

It helps reduce self interference in full duplex systems by directing reflections away from the receiver chain and toward regions where jamming is desired.

It improves energy efficiency of jamming, since the surface itself is largely passive and consumes far less power than active radios.

Practical Considerations

RIS introduces its own challenges. Hardware imperfections, control signaling overhead, and placement constraints can limit performance. Malicious or unauthorized RIS installations can also be used by attackers to redirect signals or amplify eavesdropping capabilities. Therefore, RIS infrastructure must be authenticated and managed securely.

Standardization and integration into existing 5G deployments are still emerging topics. Early adoption will likely appear in controlled environments such as factories, campuses, or critical facilities, where RIS placement and management can be tightly controlled.

Hybrid Cryptographic and Physical Layer Security

Technical Approach

Relying entirely on physical layer security is risky, especially when channel conditions or hardware limitations reduce its effectiveness. A more balanced approach is to combine friendly jamming with lightweight cryptographic mechanisms in a layered way (Li et al., 2025).

The basic idea is to adjust the security stack to the sensitivity of the data and the latency budget of the application:

1. For the most delay sensitive traffic, use physical layer methods with very light cryptographic protection, such as short authentication tags or streamlined key confirmation.

2. For traffic that is slightly less sensitive to delay, combine friendly jamming with efficient symmetric encryption.

3. For traffic without strict URLLC constraints, use full strength modern cryptography, possibly including post quantum algorithms.

Quantum key distribution can also be used on fixed links between core network nodes to create strong keys, which then protect URLLC segments where friendly jamming is used mainly as an extra line of defense.

Mitigation Effect

A hybrid approach reduces the risk that a weakness in any single layer leads to complete compromise. If physical layer protection becomes ineffective in a certain scenario, cryptographic protection still stands. At the same time, physical layer techniques make it harder for attackers to collect large volumes of clean ciphertext for future offline attacks.

This combination is also useful in the face of future quantum computers. Even if current public key algorithms are broken, physical layer protection and symmetric schemes with long keys can still offer meaningful resistance.

Practical Considerations

Designing hybrid protocols requires careful attention to key management, negotiation of security levels, and avoidance of downgrade attacks, where an adversary forces two parties to agree on a weaker protection mode. Hardware acceleration for symmetric algorithms and lattice based post quantum schemes can help keep latency within URLLC budgets.

Legacy devices that cannot support advanced physical layer features will have to rely more on cryptography, so compatibility and graceful fallback mechanisms are necessary.

Multi UAV Cooperative Jamming

Technical Approach

UAV platforms can act as mobile jamming and relay nodes. Due to their altitude and mobility, they can create favorable geometric conditions for friendly jamming, for example by maintaining line of sight links to both legitimate receivers and potential eavesdroppers (Ahmed & Khosravirad, 2024; Wang et al., 2024; Zhang et al., 2024).

In cooperative setups, one UAV may function mainly as an aerial base station, while others provide jamming support. Joint optimization techniques can determine their trajectories, power levels, and scheduling to maximize secrecy rate while respecting energy and flight constraints.

Mitigation Effect

UAV based jamming helps compensate for lack of precise channel knowledge by adjusting position until effective interference patterns are observed. It also allows dynamic reconfiguration in response to mobile eavesdroppers.

Because UAVs operate above many obstacles, they can disrupt eavesdropping based on reflections or shadowed regions that ground jammers cannot easily reach.

Practical Considerations

Regulation is a major factor. Airspace rules, privacy concerns, and safety requirements restrict where and how UAVs can fly, especially over populated areas. UAV failures can have physical consequences, so safety systems and redundancy are essential.

Operating UAV fleets for security purposes also introduces cost. It may be justified for military, governmental, or high value industrial deployments, but it is less likely to be used for everyday consumer services.

Feasibility and Broader Implications

Resource Constraints

Friendly jamming and the proposed mitigation strategies place nontrivial demands on power, spectrum, and computation. AI based solutions require training and inference resources. RIS and UAV solutions require hardware investment and maintenance.

For small IoT devices, offloading complex decision making to edge servers is often the only realistic option. For battery powered platforms, aggressive jamming needs to be balanced with duty cycling, energy harvesting options, and careful power management.

Spectrum is another limiting factor. Regulators may be cautious about technologies that intentionally generate interference, even if it is considered friendly in context. Coordination across different systems and operators is needed to avoid harmful interference.

Scalability

URLLC deployments often involve a large number of devices. Any friendly jamming strategy must scale without overwhelming control channels or management systems. Hierarchical designs, where local controllers manage clusters of devices and jammers, can help.

AI based solutions also raise questions about how many separate models are needed, how often they must be retrained, and how to distribute updates. Techniques such as federated learning and transfer learning can reduce overhead by sharing knowledge across similar deployments (Anthropic, 2024).

Infrastructure Compatibility

Friendly jamming must coexist with existing 5G infrastructure and standards. Network slicing offers one possible integration point, allowing URLLC slices to use specific physical layer security features without affecting other slices. However, radio access network equipment may need upgrades to support full duplex, extra antennas, or RIS interfaces.

Mixed environments with both new and legacy devices will be common for many years. Security frameworks must therefore support different capability levels while avoiding weak link effects where an attacker targets the least protected part of the system.

Privacy and Ethics

Jamming, even if friendly, can affect unintended receivers. It may interfere with neighboring networks or devices that are not part of the security policy. This raises regulatory and ethical questions, especially when critical public services or emergency communication could be impacted.

Collecting detailed channel and location information for jamming optimization also has privacy implications. Operators need clear policies on data collection, retention, and sharing. Techniques for privacy preserving analytics, such as differential privacy or federated learning, can help reduce risk.

There is also a dual use concern. Techniques that make friendly jamming more effective can also make malicious jamming more dangerous. Proper access control, auditing, and possibly legal oversight are necessary to prevent abuse.

Communication of Technical Recommendations

When communicating these technical recommendations to non expert audiences, visual aids can help make complex ideas clearer. Three types of diagrams or charts are especially useful:

1. System level block diagrams

   These show the relation between transmitter, receiver, friendly jammer, eavesdropper, RIS panels, and possibly UAV nodes. Search phrases you can use include:

   friendly jamming system model diagram

   physical layer security block diagram

   RIS assisted secure communication illustration

2. Flow charts for decision logic

   These can illustrate how an AI based adaptive jammer selects actions based on observed states and rewards. Search phrases:

   reinforcement learning based jamming flow chart

   actor critic wireless jamming diagram

3. Tradeoff charts for performance and security

   For example, a plot with jamming power on the horizontal axis and secrecy rate and user throughput on the vertical axes, or a chart showing latency versus level of security. You can search for:

secrecy rate versus jamming power plot

URLLC reliability latency tradeoff chart

You can either recreate these figures yourself in a drawing tool or adapt ideas from diagrams you find in academic articles. When using figures from published papers, make sure to cite the source properly and follow your institution rules on fair use. In APA format, figures should be labeled as Figure 1, Figure 2, and so on, with a clear caption that explains what the reader should notice.

Conclusion

Friendly jamming is a promising method for improving security in URLLC applications, especially where strict delay requirements limit the use of heavy cryptographic protocols. It takes advantage of physical properties of wireless channels and can be combined with modern technologies such as beamforming, full duplex operation, RIS, and UAV platforms.

At the same time, this paper has shown that friendly jamming comes with nontrivial vulnerabilities. Imperfect channel knowledge, self interference in full duplex systems, and resource allocation conflicts all create opportunities for attackers and practical obstacles for defenders.

Mitigation strategies that combine AI based adaptation, RIS integration, hybrid cryptographic and physical layer protection, and multi UAV cooperation can significantly reduce these risks. However, they also introduce new requirements in terms of computation, energy, hardware complexity, and regulatory compliance.

Looking ahead toward 6G, physical layer security is likely to become more tightly integrated into network design, rather than added on later. Technologies such as terahertz communication, integrated sensing and communication, and quantum enhanced methods will open new possibilities for friendly jamming and related techniques.

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