Adaptive Scheduling Strategies for Radar-5G Coexistence: A Symbol-Level TTI Approach

Abstract—**This paper presents a novel simulation framework and analytical model to address the challenges of radar interference in 5G Time Division Duplexing (TDD) systems, with an emphasis on symbol-level Transmission Time Interval (TTI) configurations. The proposed framework quantifies the performance trade-offs associated with dynamic TTI adjustments under radar interference, focusing on critical metrics such as collision probability, retransmission rates, and throughput efficiency. By simulating radar-5G coexistence at the symbol level, we demonstrate that shorter TTIs significantly mitigate radar-induced collisions, enhancing system reliability in interference-heavy environments. However, these improvements do come at the cost of increased control overhead and reduced throughput efficiency, underscoring the need for adaptive scheduling strategies. The results demonstrate that symbol-level TTI adjustments can optimize spectrum utilization, enhance fairness, and improve robustness in shared spectrum deployments, offering actionable insights for designing adaptive 5G systems to achieve efficient radar-5G coexistence.**

Index Terms—**5G, Radar, DL, UL, Scheduler, MAC, MCS, CQI, Spectrum, CoExistance, Symbol, TTI, Matlab, Model, Harq**

I. Introduction

The growing demand for efficient spectrum utilization has made the coexistence of 5G and radar systems in shared frequency bands, such as the Citizens Broadband Radio Service (CBRS) band, a pressing challenge [1], [2]. This coexistence is particularly critical in bands also occupied by high-power radar systems, including military radars like the SPN-43 air traffic control radar [3], [4]. Radar signals can severely disrupt 5G Time Division Duplexing (TDD) systems, which rely on the same frequency for uplink and downlink, creating susceptibility to external interference. As 5G supports mission-critical applications such as autonomous systems and industrial IoT, ensuring reliable communication in shared spectrum environments is imperative.

A promising solution lies in symbol-level scheduling, a feature of 5G TDD systems that enables fine-grained resource allocation compared to traditional slot-based scheduling. This granularity allows dynamic adjustments to Transmission Time Interval (TTI) configurations, reducing radar interference. However, implementing symbol-level scheduling is non-trivial, introducing challenges such as managing collision probabilities, retransmissions, and fairness among users. While prior studies have explored radar interference, most focus on slot-based scheduling or high-level system impacts, leaving a significant gap in understanding the potential of symbol-level scheduling for interference mitigation. Additionally, simulation tools that quantify symbol-level performance under realistic shared spectrum conditions remain scarce.

This paper addresses these gaps by introducing a novel simulation framework that models radar interference at the symbol level in 5G TDD systems. The platform facilitates an in-depth analysis of dynamic scheduling strategies, TTI configurations, and channel conditions, providing insights into key performance metrics such as throughput, retransmission rates, and collision probability. Unlike prior works that emphasize static or slot-level strategies, our study captures the dynamic interactions between radar pulses and 5G transmissions, offering actionable insights into effective coexistence mechanisms.

The overarching goal of this research is to evaluate how dynamic TTI scheduling can enhance 5G performance in radar coexistence scenarios, ultimately achieving improved spectrum utilization. Our framework tests the hypothesis that dynamic TTI adjustments can reduce collision probability and retransmission rates, thereby improving system efficiency against certain radar profiles. Furthermore, the analysis reveals critical trade-offs: shorter TTIs offer higher resilience to interference but introduce scheduling overhead, whereas longer TTIs maximize throughput under low-interference conditions but are more vulnerable to disruption.

This work makes the following contributions:

- **Simulation Framework**: A symbol-level simulation platform for modeling radar-5G coexistence scenarios.
- **Performance Analysis**: Insights into TTI configurations and their impact on system efficiency, sustainability, and robustness.
- **Practical Implications**: Demonstrating the potential of symbol-level dynamic TTI allocation to improve performance and stability in shared spectrum environments.

By addressing the limitations of existing approaches, this paper provides a deeper understanding of symbol-based TTI strategies and their practical application to enhancing radar-5G coexistence.

II. Related Work

The coexistence of radar and 5G systems in shared spectrum environments has been a prominent area of research, with numerous studies analyzing the mutual impact of interference. For example, [5], [6], and [7] examine the degradation of the 5G system performance caused by radar signals, highlighting issues such as reduced throughput and increased error rates. In contrast, studies such as [8] and [9] focus on the effects of 5G interference on the performance of the radar system, underscoring the bidirectional nature of the challenge of co-existence.

Although these studies provide valuable information on the impacts at the system level, they often overlook the role of scheduling strategies in mitigating interference. A key advancement in 5G compared to 4G is the introduction of symbol-based scheduling [10], [11], which allows for a finer allocation of resources than the slot-based scheduling used in 4G [12], [13]. Symbol-based scheduling allows for more precise interference management by dynamically adjusting resource assignments, making it a promising technique for reducing periodic short bursts of radar interference.

Symbol-based scheduling also brings the flexibility to adapt Transmission Time Intervals (TTI), which can minimize the duration of vulnerable transmission blocks and reduce the overlap between radar pulses and 5G transmissions. Advanced techniques, such as the integration of xAPPs and Edge Computing, further enhance the potential of symbol-based scheduling by enabling real-time adaptive interference avoidance strategies. These innovations present opportunities for significant performance improvements, particularly in shared spectrum environments.

Recent research has explored specific aspects of symbol-based scheduling. For example, [14] and [15] investigate machine learning approaches for real-time symbol scheduling, while [16] studies the impact of symbol-based allocation on uplink performance in network slicing. Furthermore, studies such as [17] evaluate the benefits of TTI adjustments for traffic management, demonstrating the potential of dynamic scheduling to improve performance metrics.

Despite these advances, there is a lack of comprehensive research that focuses on the effectiveness of symbol-based scheduling to mitigate radar interference. Existing studies primarily address high-level system impacts or focus on slot-based scheduling strategies, leaving a significant gap in understanding how symbol-level scheduling can improve radar-5G coexistence. Furthermore, robust simulation tools are scarce to evaluate symbol-level interference and scheduling techniques under realistic conditions.

This paper addresses these gaps by presenting a detailed analysis of symbol-level scheduling strategies for 5G TDD systems in shared spectrum environments. Our simulation platform models radar interference at the symbol level and evaluates the impact of various scheduling strategies on critical performance metrics, including throughput, retransmission rates, and collision probability. By providing novel insights into the trade-offs and potential of symbol-based scheduling, this work contributes practical solutions to improve spectrum sharing and interference mitigation in 5G networks.

III. Foundational System Model and Simulation Design

Radar transmissions often overlap with the serving cell of a 5G TDD network, causing significant interference for User Equipment (UEs) and disrupting critical functionalities such as resource scheduling and data transmission. These challenges are particularly severe in environments with high-power radar signals, which can overwhelm 5G transmissions. To address these issues, we developed a simulation platform to model radar interference at the symbol level in 5G TDD systems, enabling the quantification of performance impacts and the exploration of mitigation strategies.

The simulation platform, implemented using MATLAB's Wireless Network Simulator, is designed to

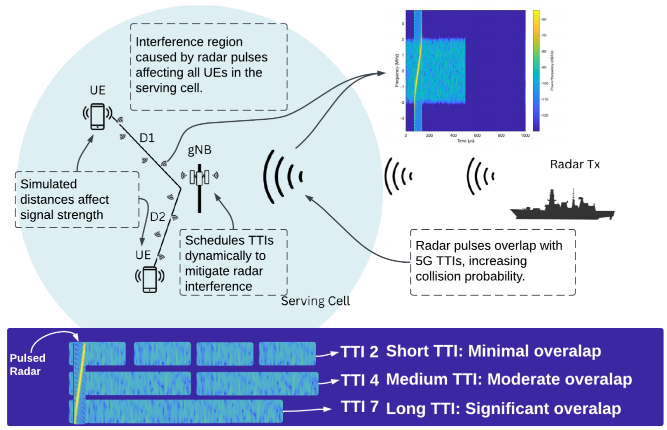

Fig. 1: Platform of Con-Ops of High Power Radar Interference on a 5G TDD Cell

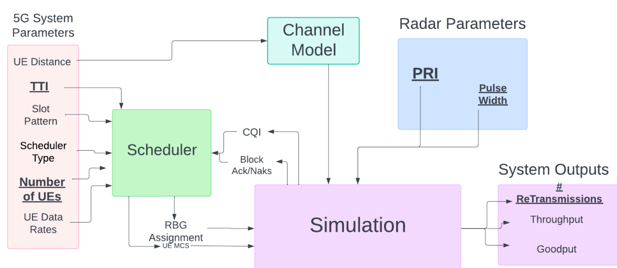

Fig. 2: Fig. 2: Simulation IO Overview: Structure of the simulation platform highlighting inputs, the scheduler, and key system outputs.

analyze the coexistence of 5G and radar systems. As shown in Figure 2, the simulation model incorporates multiple inputs and outputs to evaluate system performance. This investigation focuses on analyzing the impact of TTI adjustments with varying numbers of UEs, while other parameters in the model remain static. The framework enables a detailed exploration of symbol-level scheduling strategies under different interference scenarios, including

- Configurable Transmission Time Interval (TTI) schemes,
- Adjustable radar parameters, such as pulse width (τ_r) and Pulse Repetition Interval (PRI),
- Advanced logging capabilities for key performance metrics: throughput, retransmission rates, and collision probability.

The coexistence scenario modeled by our Concept of Operation (Con-Ops) platform is illustrated in Figure 1. As shown, radar transmissions overlap with the 5G TDD serving cell, creating an interference region that impacts all connected User Equipment (UEs). The platform quantifies this interference and evaluates mitigation strategies such as dynamic TTI scheduling. Additional insights into the radar-5G interaction dynamics and performance metrics, including collision probabilities and retransmission rates, are detailed in the figure.

The proposed simulation platform is designed to model radar-5G coexistence at the symbol level, enabling detailed exploration of Transmission Time Interval (TTI) configurations and their impact on system performance. By providing fine-grained control over scheduling parameters, the platform allows for the evaluation of interference mitigation strategies under various radar and 5G scenarios.

A. *Symbol-Level Collision Probability Model*

a) Model Overview: To address the challenges of radar-5G coexistence, we propose a symbol-level analytical model that captures the interaction dynamics between radar pulses and 5G Time Division Duplexing (TDD) transmissions. This model provides a practical framework for evaluating the impact of Transmission Time Interval (TTI) configurations on collision probability, retransmissions, and overall system efficiency.

The model assumes deterministic radar parameters, including:

- Pulse Width (τ_r): Duration of each radar pulse.
- Pulse Repetition Interval (PRI, T_r): Time between consecutive radar pulses.

The TTI duration, T_{TTI}, is determined by the number of symbols (N_{TTI}) within the TTI:

$$T_{TTI} = N_{TTI} \cdot T_s,$$

where T_s is the duration of a single 5G symbol. Short TTIs correspond to low N_{TTI}, offering finer granularity but increasing control overhead, while long TTIs correspond to high N_{TTI}, maximizing throughput but increasing susceptibility to radar interference.

b) Collision Probability: Collision occurs when radar pulses overlap with any portion of a TTI. The collision probability, $P_{\text{collision}}$, quantifies the fraction of the TTI duration affected by radar interference:

$$P_{\text{collision}} = \frac{\text{Overlap Duration}}{\text{TTI Duration}}.$$

The collision probability is defined as:

$$P_{\text{collision}} = \begin{cases} \frac{T_{TTI}}{T_r} & \text{if } T_{TTI} < \tau_r, \\ \frac{\tau_r}{T_r} & \text{if } T_{TTI} \geq \tau_r. \end{cases} \quad (1)$$

where T_r is the radar Pulse Repetition Interval (PRI). This equation captures the following scenarios:

- **Short TTI** ($T_{TTI} < \tau_r$): The entire TTI is affected by radar pulses. In this case, reducing T_{TTI} minimizes the fraction of time impacted by interference.
- **Long TTI** ($T_{TTI} \geq \tau_r$): Only a portion of the TTI overlaps with radar pulses. Here, the collision probability saturates at $\frac{\tau_r}{T_r}$, making it independent of T_{TTI}.

c) Impact on Retransmissions and Quality: The collision probability directly impacts retransmission rates (R_{retrans}), as collisions degrade packet delivery. Retransmissions increase latency and reduce throughput, negatively affecting the system's Quality of Service (QoS). The retransmission rate is proportional to the collision probability:

$$R_{\text{retrans}} \propto P_{\text{collision}}.$$

By optimizing T_{TTI} to minimize $P_{\text{collision}}$, the system can achieve:

- Reduced retransmissions, improving latency and efficiency.
- Improved robustness to radar interference, enhancing communication reliability.
- Balanced throughput and fairness across users through adaptive scheduling.

d) Optimizing TTI Strategy: The model highlights the trade-offs in selecting the optimal TTI duration:

- **Short TTI:** Low N_{TTI} reduces collision probability and enhances resilience to interference. However, frequent scheduling introduces higher control signaling overhead.
- **Long TTI:** High N_{TTI} maximizes throughput in low-interference scenarios but increases collision probability under radar interference.

The optimal T_{TTI} balances collision reduction and control overhead:

$$T_{TTI}^* = \text{argmin}_{T_{TTI}} \big(P_{\text{collision}} + \lambda \cdot \text{Overhead Cost}\big),$$

where λ is a weighting factor reflecting the trade-off between robustness and efficiency.

IV. Dynamic and Stochastic Model for Radar-5G Coexistence

A. Limitations of the Foundational Model

The simplified collision probability model assumes deterministic radar parameters and perfect synchronization between radar pulses and Transmission Time Intervals (TTIs). While effective for establishing foundational insights, it fails to account for the dynamic and stochastic nature of real-world radar-5G coexistence. Specifically, the simplified model:

- Ignores stochastic variations in radar Pulse Width (PW) and Pulse Repetition Interval (PRI), which can significantly impact collision dynamics.
- Assumes static TTI configurations, overlooking the potential of adaptive scheduling to mitigate interference in real time.
- Does not incorporate feedback mechanisms, such as Hybrid Automatic Repeat Request (HARQ), which influence retransmissions.
- Lacks multi-dimensional optimization, focusing solely on collision probability without balancing throughput, latency, and fairness.

These limitations necessitate a more comprehensive approach that incorporates the stochastic nature of radar interference and dynamic system behavior.

B. Proposed Complex Model

The complex model extends the simplified framework by addressing its limitations through a stochastic and dynamic approach to collision probability estimation.

1) Dynamic Overlap Function: The collision probability $P_{\text{collision}}$ is computed based on a time-varying overlap between radar pulses and 5G TTIs:

$$P_{\text{collision}} = \frac{1}{T_{TTI}} \int_{t=0}^{T_{TTI}} \mathbb{I}(\text{Radar Active}(t) \cap \text{Symbol Active}(t))\, dt. \quad (2)$$

where $\mathbb{I}$ is an indicator function that evaluates whether a radar pulse and a 5G symbol overlap at time t. This dynamic approach captures the variability in radar pulse timing and symbol alignment.

2) Stochastic Radar Parameters: To model real-world scenarios, the radar pulse width (τ_r) and PRI (T_r) are treated as random variables with probability density functions $p(\tau_r)$ and $p(T_r)$, respectively. The expected collision probability is then calculated as:

$$P_{\text{collision}} = \int_0^\infty \int_0^\infty \frac{\min(T_{TTI}, \tau_r)}{T_r} \cdot p(\tau_r) p(T_r)\, d\tau_r\, dT_r.$$

3) Feedback Mechanisms: The model incorporates real-time feedback from system-level metrics, such as retransmissions and channel conditions. The collision probability becomes a function of past and predicted system states:

$$P_{\text{collision}} = f(P_{\text{collision, past}}, R_{\text{retrans, current}}, T_{TTI,adaptive}).$$

4) Multi-Objective Optimization: To balance collision probability with system performance metrics, the model formulates an optimization problem:

$$\text{Minimize: } \alpha \cdot P_{\text{collision}} + \beta \cdot \text{Retransmission Rate} + \gamma \cdot \text{Latency},$$

where α, β, and γ are weighting factors reflecting the trade-offs between interference mitigation, efficiency, and fairness.

V. Selection Criteria for Radar Characteristics

Many radar systems today use a form of Pulse manipulation to increase range resolution. This is also referred to as pulse Compression. A good example of this is Linear Frequency Modulation. In our research of radar systems such examples of Frequency Modulated Radar system are widespread[18] with over 20 systems identified, and are relatively easy to simulate with Matlab[19]. Selecting a Frequency Modulated radar signal also introduced a the characteristic of frequency bandwidth to the available variables to test. Leveraging online databases such as [18], an assessment of radar systems operating inside band 78 was conducted. We identified over 20 unique systems covering S-Band. Some radar systems inside the database have specific and unique values, while other are more broad. Some of the online identified radar systems are likely no longer in operation. However, the PRF, Pulse Duration, Frequency operation, and other characteristics identified allows us to target a common range of values for analysis. Large simulation ranges of the radar characteristics were selected for the simulation to remove bias and better understand the impacts without focusing on any one specific radar systems. For the operational modulation bandwidth of the radar pulse the values selected to test various overlapping scenarios to the 5G Transmitted Signal.

We have identified the following ranges of values:

- PRF:
- PulseWidth:
- Modulation BandWidth:
- Modulation BW Offset:
- Radar Attenuation:

VI. 5G Throughput analysis based on isolated Radar Parameters

We look to identify which interference parameters achieve the largest impact to 5G signals. In the follow experiments we isolate each of the following:

- **PRF Pulse Repetition Function**: Described in Hz this is the interval between each radar pulse.
- **Pulse Duration**: This is the timing duration of the pulse in µS
- **Pulse BW**: The radar pulse is frequency modulated to cover a BW (Band Width) in MHz. For example if the Duration is 100S, and the BW is 5MHz, the pulse will sweep 5MHz of frequencies inside that duration.
- 5G **Radar Power influence**: Here we investigate what Ratio of Radar to 5G Signals generate the most influence. E.g. How strong of a radar signal is required to influence the 5G throughput.

A. Expected Throughput Results without radar interference

Based on the simulation parameters in Table IV the throughput for the 20MHz cell with slot based scheduling with the max supported MCS of 27 is $84.2Mbps$. However in our simulation the UEs were at a distance of 300M which produced an average MCS for the simulation duration across all 20 UEs of roughly 24.3 in the DL. A MCS of 24 or 25 Produces an expected throughput of $74.7Mbps$ or $78.6Mbps$. Our simulation results (Avg 24.3 MCS) for slot based to fell within these two values with an average of $3.78Mbps$ for each of the 20 simulated users and a total throughput of: $20UEs \times 3.78Mbps = 75.6Mbps$. For TTI based scheduling the following simulated results were found as the expected throughput for each user without radar interference are found in table I. These values are considered best case and will be used as a reference point of comparison for the other simulations performed.

TABLE I: Avg Expect Throughput per UE without radar interference

TTI	Avg Throughput Without Interference
TTI = 2	0.496696 (Mbps)
TTI = 4	2.081720 (Mbps)
TTI = 7	3.430896 (Mbps)
TTI = 14 (Slot Based)	3.785808 (Mbps)

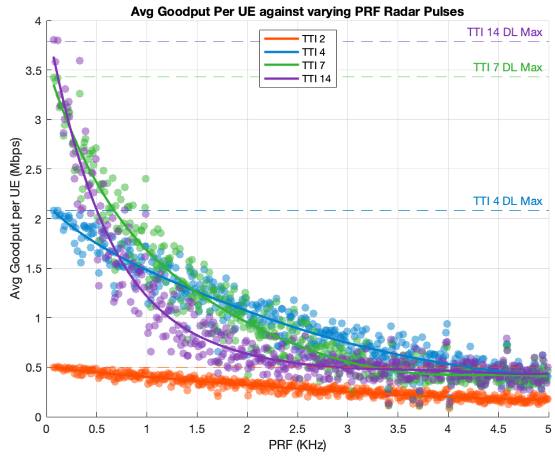

Fig. 3: prf vs DL goodput bps20MHzPulseBW 3

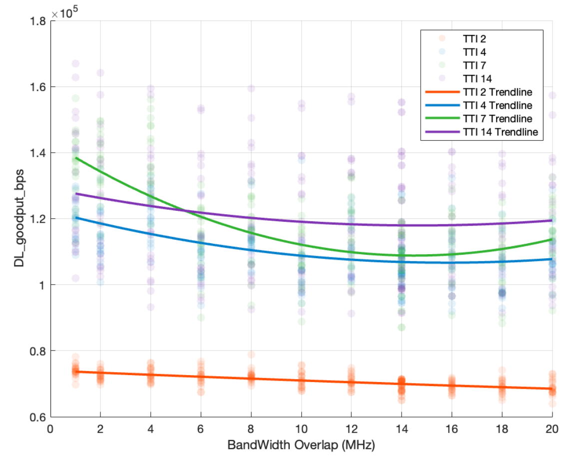

Fig. 5: BW Coverage Throughput

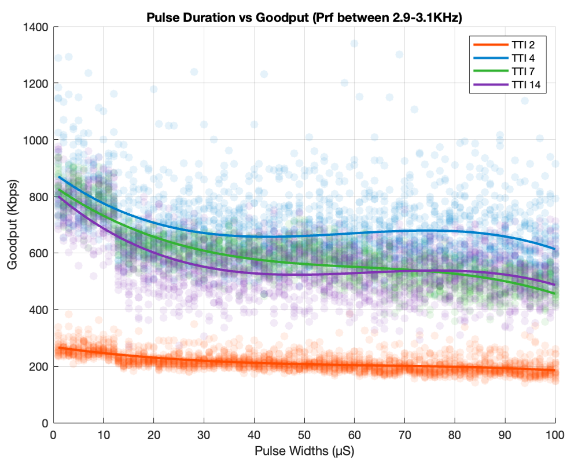

Fig. 4: goodput v pulseDuration

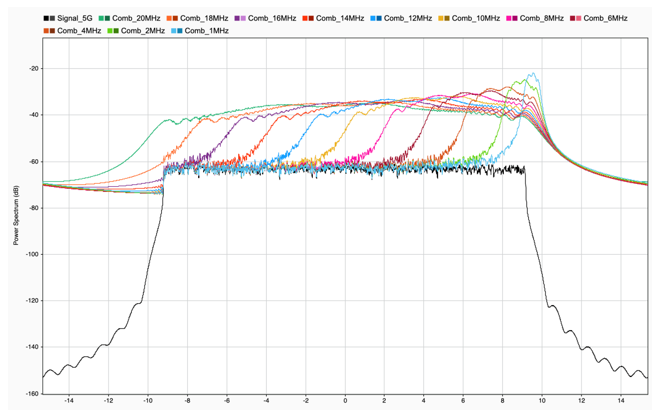

Fig. 6: RadarBWs v 5GSignal

B. Pulse Repetition Function Influence

C. Pulse Duration Influence

In this example the PRF is set to a constant 2KHz

D. Pulse Bandwidth

Overlap Percentage: This is the amount of overlap in Frequency the radar pulse has over the 5G signal. The question here is that does a larger BW radar cause more interference than a smaller BW radar. Or put another way can a small 1MHz radar pulse at the edge of the 5G Cell Spectrum be just as disruptive as a large wideband radar pulse. Here we try to answer how much overlap of the 5G Radar causes influence.

Need to update this picture to include the average for each TTI. The varaiance between each RNTI in the run is large making the Trendline hard to fit.

E. Radar Power Influence

Here we try to understand how much a strong or a weak 5G signal plays influence on the throughput of the cell. In this isolation experiment the radar is set to be 20MHz and the power is varied from a max power level of -17dBm to -137dBm. The 5G Signal mean power level remains constant at roughly -60dBm.

VII. Relationship between ReTx and Throughput and Goodput

This is an optional section but might help with something else. Is the overall objective to reduce the retTx or from the user perspective its likely throughput. There is likely a measurable understanding of knowing the reTx percentage as it increases the difference between the goodput and throughput changes.

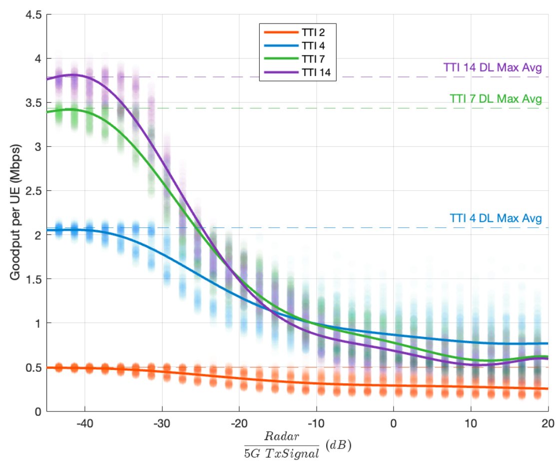

Fig. 7: goodput v radarAtten for PRF values between 2990 and 3010 Hz

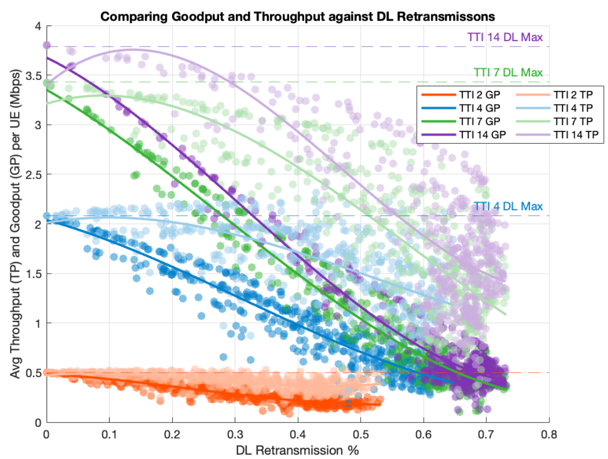

Fig. 8: Enter Caption

VIII. Experimentation Results

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A. Simulation Parameters and Configurations

Two major simulations were conducted to quantify the effects of TTI variance alongside interference. The first simulation focused on the variation in TTI in relation to a fixed narrow Pulse Width (PW), less than a single symbol and less than each evaluated TTI. The second simulation was a much larger run where the Pulse Width and pulse index were randomly varied for each run. Simulation 2 aimed to identify the impacts of Pulse Widths as they relate to TTIs.

In Simulation 1, the model was run with varying numbers of UEs: 5, 10, 15, and 50, for TTIs of 2, 4, and 7, respectively. This was done to minimize any abnormalities that could occur due to scheduler distributions. Each simulation ran for 100 frames, with static interference throughout. The interference pulse was fixed such that the second symbol was always targeted within the slot. The second symbol of interference is highlighted in Figure 9.

In Simulation 2, TTIs of 2 and 4 were evaluated across 150 scenarios, with the number of UEs fixed at 10 for each evaluation. The simulation randomly varied the radar Pulse Width between 5 and 500 µS, and the start index of the pulse was varied randomly between 1 and 500 µS.

The physical layer parameters used are shown in Table II. A subcarrier spacing (SCS) of 15 kHz was chosen, corresponding to a 1 ms slot duration, which aligns with the AN/SPN-43 radar's 1 ms Pulse Repetition Interval (PRI) [18]. This alignment ensures radar pulses synchronize with 5G slot boundaries, allowing accurate modeling of interference dynamics.

TABLE II: PHY Layer Parameter Settings Need to redo or remove for 30KHz scs

Parameter	**Values**
Symbol Lengths Including CP	71.9 or 71.4 (µS)
TTI = 2 Duration	≈ 143 (µS)
TTI = 4 Duration	≈ 286 (µS)
TTI = 7 Duration	≈ 500 (µS)
Nfft	512
Sub Carrier Spacing	15 KHz
Sample Rate	7680000
Symbols Per Slot	14
Slots Per Subframe	1
Slots Per Frame	10

The static configuration values for the gNB used in each simulation run are summarized in Table IV.

Supported Bandwidths for B78 Comparing Radar PRF, PW, BW

IX. Simulation and Analysis

A. Impact of Symbol-Level TTI Strategies on Radar Interference

To quantify the effects of radar interference on 5G transmissions, block collision percentages were calculated using the simplified model described in Sec. III-A0b. Fig. 9 shows the radar interference spectrogram for TTIs of 2, 4, and 7. Key findings highlight the significant differences in interference impact across TTI configurations:

TABLE III: Simulation Run 1 Configuration Parameters

Configuration	Values
gNB Configurations	
Scheduler	Round Robin
Modulation and Coding Scheme (MCS)	Static MCS of 5 for each UE
Max HARQ	16
Sub-Carrier Spacing	15 KHz
Bandwidth	20 Resource Blocks (10 RBGs)
Slot Pattern	2D1S2U, where S is (8D2G4U)
Slot Pattern Periodicity	5 ms (10 slots per Frame with 15 KHz SCS)
UE Distance	Simulated distance of 300 m for each UE
UE BitRate	10 Mbps in both DL and UL directions
Radar Configurations	
Radar Pulse Width	60 μs
Radar Periodicity	1 ms
Radar Bandwidth	5 MHz
Radar Offset	Symbol index 2 [1..14] was intefered with x

TABLE IV: Simulation Run 30KHz Configuration Parameters

Configuration	Values
gNB Configurations	
Scheduler Type	Round Robin
Modulation and Coding Scheme (MCS)	Dynamic / LA Enabled
Max HARQ	16
Sub-Carrier Spacing	30 KHz
Bandwidth	20 MHz (51 PRBs)
Slot Pattern	7D1S2U, where S is (8D2G4U)
Slot Pattern Periodicity	5 ms
TTI	rand(2,4,7, or slot based)
MCS Table Used	3GPP 38.214 Table 5.1.3.1-2 (256QAM)
UE Configurations	
Number of UE	20
UE Distance (each)	300 m
UE BitRate	10 Mbps in both DL/UL
Radar Configurations	
Radar Distance km	?
Radar Power [EIRP] kW	?
Radar Pulse Width (PW)	rand(0.1 : 100) μs
Radar Periodicity (PRF) Hz	rand(500:5000) Hz
Radar Start Offset	rand(0:250) ms
Radar Offset from Center	rand[1 2 5 10 20] MHz
Radar Bandwidth	rand[0 1 2 5 10 25] MHz

- **TTI = 7:** Approximately 50% of symbols were impacted, as the longer TTI duration increases the likelihood of overlapping with radar pulses. This results in a higher collision probability and a higher number of retransmissions.
- **TTI = 4:** About 25% of symbols were impacted, demonstrating a moderate collision probability and retransmission rate.
- **TTI = 2:** Only 14.2% of symbols were impacted. The shorter TTI duration reduces the window of vulnerability to radar interference, leading to fewer collisions and retransmissions.

These results confirm that shorter TTIs significantly reduce collision probabilities, mitigating radar interference. However, they also introduce higher control overhead, potentially reducing throughput efficiency in interference-free scenarios.

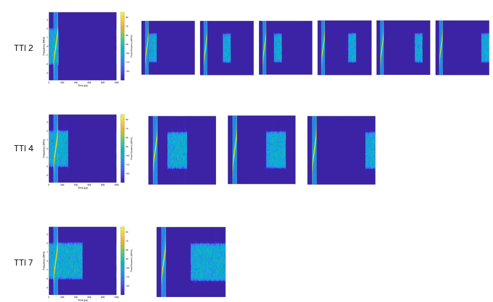

Fig. 9: Spectrogram of Radar Interference for TTIs 2, 4, and 7.

Symbol-Level TTI and Improved Spectrum Utilization: Symbol-level TTI adjustments provide a more granular approach to managing resources and interference compared to traditional slot-level scheduling. By dynamically adapting TTI configurations at the symbol level, the system can significantly improve spectrum utilization in the following ways: Shorter TTIs minimize collision probability by ensuring that radar pulses impact fewer symbols within each TTI. For instance, with a TTI of 2, the duration of the radar-affected window is significantly smaller compared to a TTI of 7, reducing the likelihood of collisions and leading to fewer retransmissions. This improvement directly enhances the utilization of available spectrum resources. Furthermore, collision-free symbols in shorter TTIs can be successfully transmitted without requiring retransmissions, which improves spectral efficiency. In contrast, longer TTIs are more prone to retransmissions due to their higher collision probabilities, resulting in wasted time and spectrum resources. Symbol-level granularity further enhances system performance by allowing the scheduler to dynamically allocate resources to radar-free symbols, effectively avoiding radar-affected symbols. This adaptability is not achievable with traditional slot-level TTIs. Moreover, by steering clear of radar-impacted symbols, symbol-level scheduling promotes better resource fairness among UEs, ensuring that no individual user experiences disproportionately high retransmissions or delays. These advantages collectively demonstrate the effectiveness of symbol-level TTI strategies in improving spectrum utilization and system performance in radar-5G coexistence scenarios.

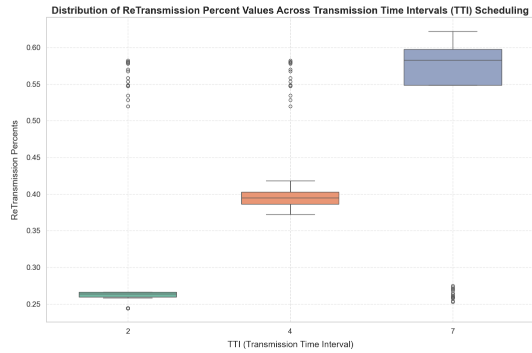

Fig. 10: Box Plot of Retransmission Percentages Across TTIs.

B. *Retransmission Percentages Across TTIs*

Fig. 10 presents the retransmission percentages observed during interference testing for different TTI configurations. Short TTIs (e.g., TTI = 2) demonstrated significantly fewer retransmissions due to their reduced collision probabilities. This reduction arises because shorter TTIs minimize the overlap between radar pulses and transmission blocks, allowing more packets to be delivered successfully on the first attempt. Conversely, longer TTIs (e.g., TTI = 7) showed substantially higher retransmission rates, as the increased duration of each TTI leads to greater vulnerability to radar interference.

Discrepancies between the observed retransmissions and the predictions from the simplified model in Sec. III-A can be attributed to the behavior of Hybrid Automatic Repeat Request (HARQ) procedures. In cases of interference, the same block may encounter repeated collisions, leading to multiple retransmission attempts. These additional retransmissions are not captured in the simplified model, which assumes a single retransmission per collision. This discrepancy highlights the importance of considering HARQ dynamics when evaluating system performance under interference.

The retransmission percentages directly impact system performance metrics such as throughput and latency. Lower retransmissions observed with shorter TTIs (e.g., TTI = 2) improve spectral efficiency by minimizing redundant transmissions. However, the increased control signaling associated with frequent retransmissions in longer TTIs (e.g., TTI = 7) reduces overall efficiency and increases latency. Fig. 10 illustrates these trends, with the spread of retransmissions widening for longer TTIs, reflecting their susceptibility to radar interference.

These findings underscore the importance of selecting TTI configurations based on application-specific requirements. For interference-heavy environments, shorter TTIs offer a clear advantage in minimizing retransmissions and improving reliability, albeit at the cost of increased control overhead.

C. *Throughput Analysis*

Fig. 11 presents the downlink throughput and resource share percentages for five UEs across different TTI configurations, both with and without radar interference. This analysis highlights the interplay between TTI settings and system performance in terms of throughput efficiency, resource allocation fairness, and resilience to interference.

With the shortest TTI (TTI = 2), the system demonstrates high resilience to interference, as evidenced by the stable throughput across UEs even under radar conditions. The dynamic allocation of shorter TTIs allows for effective avoidance of radar-affected symbols, resulting in minimal retransmissions. Furthermore, resource share among UEs remains highly uniform, indicating fairness in allocation. However, the increased control overhead associated with frequent scheduling decisions limits the overall cell-level throughput. This configuration makes TTI = 2 particularly suitable for interference-prone environments requiring reliable communication, though it is less ideal for high-throughput applications.

In contrast, the longest TTI configuration (TTI = 7) achieves the highest overall cell-level throughput in interference-free scenarios due to reduced control overhead and the larger transmission blocks. However, under radar interference, this configuration becomes highly sensitive, leading to noticeable variability in

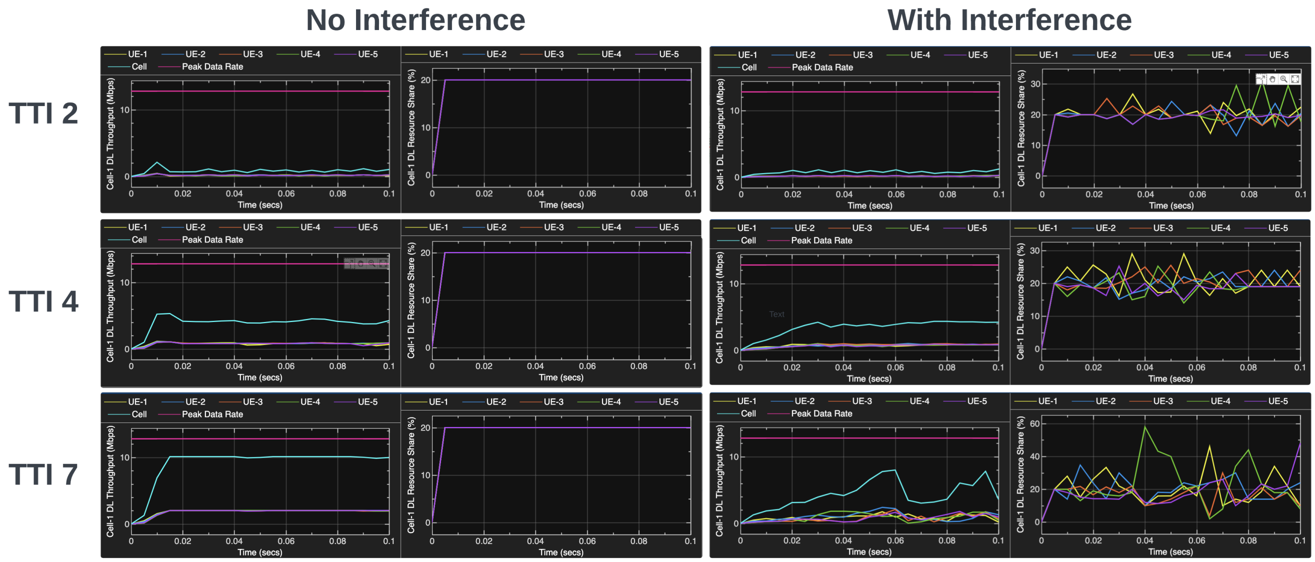

Fig. 11: Downlink Throughput and Resource Share Percentages for 5 UEs Across Various TTIs (With and Without Interference).

UE throughput and resource share. The longer TTI duration increases the likelihood of radar pulses affecting multiple symbols within each block, causing frequent retransmissions and uneven resource distribution. This makes TTI = 7 vulnerable in dynamic and interference-heavy environments but well-suited for static conditions or enhanced mobile broadband (eMBB) applications where maximizing throughput is the primary objective.

The intermediate configuration (TTI = 4) strikes a balance between throughput, fairness, and interference tolerance. While the overall throughput is lower than TTI = 7, it significantly outperforms TTI = 2 in terms of efficiency. Additionally, the resource share among UEs remains relatively stable, with only minor fluctuations observed under radar interference. This balance makes TTI = 4 a practical choice for scenarios that require moderate throughput, low latency, and robustness to interference.

Fig. 11 also highlights the resource share percentages for each UE. In the interference-free case, all TTIs exhibit an evenly distributed resource share among UEs, demonstrating the scheduler's ability to allocate resources fairly under ideal conditions. However, in the presence of radar interference, the resource distribution becomes increasingly uneven with longer TTIs. For TTI = 7, significant variations in resource allocation are observed, with some UEs receiving disproportionately higher resources while others experience reduced throughput. In contrast, TTI = 2 maintains a highly uniform resource share, underscoring its suitability for maintaining fairness in dynamic interference environments.

Radar interference primarily impacts longer TTIs, as the extended transmission duration increases the probability of symbol collisions. This results in higher retransmission rates, as shown in Sec. IX-B, and reduces effective throughput. In contrast, shorter TTIs mitigate the impact of interference by confining radar-affected symbols to smaller transmission blocks, thereby minimizing retransmissions and improving spectral efficiency. However, the trade-off lies in the increased control overhead for shorter TTIs, which can limit their effectiveness in throughput-driven applications.

The results demonstrate that TTI configuration plays a critical role in determining system performance under radar interference. While TTI = 7 maximizes throughput in ideal conditions, its sensitivity to interference makes it unsuitable for dynamic environments. Conversely, TTI = 2 ensures fairness and robustness to interference but sacrifices overall throughput due to control overhead. TTI = 4 strikes an effective balance, offering moderate throughput, low latency, and resilience to interference, making it a versatile choice for diverse operational scenarios.

D. Scheduler Behavior Under Interference

Under radar interference, resource allocation for larger TTIs (e.g., TTI = 7) became uneven due to the scheduler prioritizing retransmissions over new transmissions. Fig. 12 highlights this behavior for 15 UEs. This uneven allocation reduces system efficiency and fairness, underscoring the limitations of using larger TTIs in interference-prone environments.

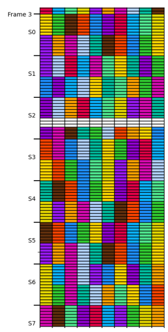

Fig. 12: Uneven Resource Allocation for TTI = 7 With 15 UEs Under Radar Interference.

Practical Gains and Trade-offs: The use of symbol-level TTI adjustments enables more efficient coexistence between radar and 5G by significantly reducing the impact of radar interference on critical transmissions. This approach allows for the optimization of available spectral resources, ensuring that fewer symbols are affected by interference, and enhances overall system robustness in interference-heavy environments. These improvements demonstrate that symbol-level scheduling is a key strategy for achieving better performance in radar-5G coexistence scenarios, particularly in challenging spectral conditions.

However, while shorter TTIs effectively reduce collision probabilities and retransmissions, they come with trade-offs that must be carefully considered. One major drawback is the increased control overhead, as shorter TTIs require more frequent scheduling decisions. This leads to higher signaling demands, which can reduce system efficiency, especially in environments with minimal interference. Additionally, the increased control signaling can limit overall throughput efficiency, making shorter TTIs less suitable for applications that prioritize high data rates. Despite these trade-offs, the advantages of symbol-level scheduling in mitigating radar interference and improving system resilience make it a valuable tool for addressing the challenges of shared spectrum environments.

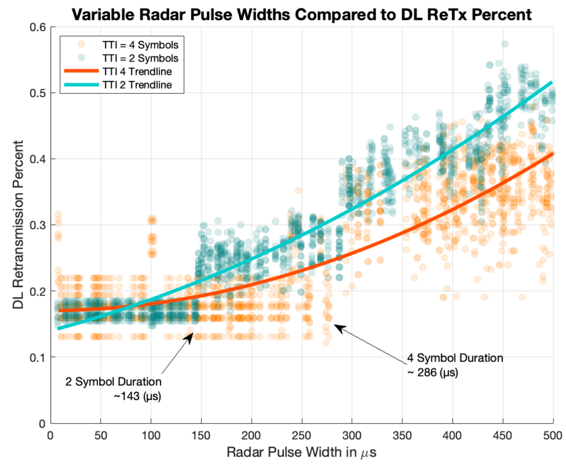

Fig. 13: 150 Simulation Run 10 UEs with random PW Variation and StartIndx against TTI's 2 and 4

E. Pulse Width Relationships to TTIs

The results of Simulation 2 are presented in Figure 13 for TTI 2 and TTI 4, respectively. Each dot represents the downlink (DL) retransmissions for a single UE during a given run. The simulation was conducted for 150 runs, with 10 UEs per run.

1) Pulse Width Less Than TTI Duration: The results of Simulation 2 show similar effects to those observed in Simulation 1 when the Pulse Width (PW) is much smaller than the Transmission Time Interval (TTI). For TTI 2, with transmission durations of approximately 143 μs, the retransmission percentage remains relatively stable and exhibits minimal variance.

In comparison, when the TTI is 4 and the Pulse Width is smaller than the TTI duration, the retransmissions are also stable and roughly predictable. However, the variance per UE is noticeably larger compared to TTI 2. These results align with the box plot observations from Simulation 1, as shown in Figure 10.

The retransmission variance is higher for TTI 4 compared to TTI 2. A detailed comparison of variances and means can be found in Table V. The mean retransmission is lowest and exhibits the least variance when both the TTI and Pulse Width are small.

2) Pulse Width Greater Than TTI Duration: The results show that when the interference Pulse Width exceeds the Transmission Time Interval, the retransmission variance increases significantly. From the graph, it can be observed that retransmissions rise quickly for TTI 2.

The simulation results in Table V show that when the TTI is 2 and the Pulse Width is greater than the TTI duration, the variance reaches 0.0012, with a higher mean compared to cases where the TTI is 4 and the Pulse Width is smaller than the TTI duration. These findings highlight the importance of considering the Pulse Width of interference when selecting an appropriate TTI value.

TABLE V: Simulation Configuration DL ReTx Results for key PW Size Intervals

TTI, Duration	**Pulse Width Between**	**Variance**	**Mean**
2, 143(μs)	≥ 0 and < 143 (μs)	0.0001	0.1690
2, 143(μs)	≥ 143 and < 286 (μs)	0.0012	0.2495
2, 143(μs)	≥ 286 and < 500 (μs)	0.0041	0.4094
4, 286(μs)	≥ 0 and < 286 (μs)	0.0014	0.1846
4, 286(μs)	≥ 286 and < 500 (μs)	0.0026	0.3464

F. PRF Influence

G. Radar Power Influence

Graph or equation about radar power showing the 30-40dB of influence radar has. When its ¿ the the 5G signal its very disruptive, and when its super less -40 from the 5G signal its not. See [redacted] The equation should be quasi linear and be based on FSPL. Something the user can reference. (E.g. 1MW radar 30Mi from the tower = X radar, 5G signal is X EIRP.... User is Y distance from the tower... If the user is this distance from the tower TTI could help if this far, doesn't matter etc...) This range shows that TTI can play a role when the power levels of the system fall within this range. A new ConOps could be drawn to highlight this range/influence.

X. Industrial Application of the Platform

Developing a simulation platform provides a practical way to study how pulsed radar signals interfere with 5G Time-Division Duplexing (TDD) systems. This platform supports various radar and communication system configurations, allowing researchers to assess performance impacts under different interference scenarios. Users can adjust radar signal characteristics and 5G system parameters to analyze the interactions between these systems, identify performance degradation, and determine operational thresholds. The presented example demonstrates the impact of different Transmission Time Intervals (TTIs) and their resilience to periodic radar signals.

A key use case is modeling the effects of diverse radar signals on 5G systems. By adjusting parameters like pulse width and Pulse Repetition Interval (PRI), researchers can quickly analyze how these factors influence 5G TDD signal performance. The platform also enables detailed analysis of 5G performance metrics such as throughput and block error rates. By varying 5G settings—including TTIs, Modulation and Coding Schemes (MCS), and Resource Block Group (RBG) allocations—researchers can identify configurations that minimize interference from radar pulses.

The platform also extends its capabilities to advanced spectrum management techniques for emerging 6G applications, such as spectrum avoidance and dynamic sharing. Features like cognitive radio, priority-based access, and machine learning-driven spectrum predictions help manage interference more effectively. These tools allow researchers to evaluate and develop advanced spectrum-sharing strategies and interference mitigation techniques for both current and future communication networks.

The platform's flexibility in supporting various TTI configurations is particularly beneficial for specific application scenarios. For instance, TTI = 2 is highly suitable for ultra-reliable low-latency communication (URLLC) applications, where consistent resource allocation and resilience to interference are critical requirements. By leveraging the platform's ability to model and analyze symbol-level interference, researchers can fine-tune scheduling strategies to optimize performance for low-latency use cases, ensuring reliable communication even in challenging interference environments. This capability highlights the potential of the platform in addressing the stringent requirements of advanced communication systems.

XI. Conclusion and Future Work

A. Summary of the Current Work

This study presents a detailed investigation into the impact of radar interference on 5G Time Division Duplexing (TDD) systems, focusing on the trade-offs between Transmission Time Interval (TTI) configurations. Simulated results, as shown in Figures 10 and 11, closely align with the mathematical predictions, demonstrating that shorter TTIs (e.g., TTI = 2) reduce retransmission rates by limiting the overlap between radar pulses and scheduled blocks. However, these configurations come at the cost of higher overhead and reduced system throughput.

Larger TTIs (e.g., TTI = 7) maximize throughput under interference-free conditions but exhibit greater susceptibility to radar disruption, resulting in uneven resource allocation and reduced fairness among users. Conversely, TTI = 4 strikes a balance, offering moderate throughput and resilience, making it a practical choice for scenarios requiring both efficiency and interference tolerance.

The results reveal that HARQ (Hybrid Automatic Repeat Request) mechanisms exacerbate retransmissions under interference, as overlapping blocks are frequently retransmitted. This contributes to the discrepancy between simulated results and idealized predictions. Despite this, the consistent resource allocation observed across UEs in interference-free scenarios underscores the robustness of the scheduling process.

Ultimately, the findings highlight the importance of tailoring TTI configurations to specific use cases. Shorter TTIs are well-suited for Ultra-Reliable Low-Latency Communication (URLLC) applications, where interference mitigation is paramount, while larger TTIs are ideal for enhanced mobile broadband (eMBB) scenarios prioritizing throughput. The balance achieved by TTI = 4 further emphasizes the need for adaptive scheduling strategies that dynamically adjust to varying interference patterns and application demands.

B. Future Directions

To address these limitations, future work will extend the model to incorporate:

- **Stochastic Radar Behavior:** Treating τ_r and T_r as random variables to capture dynamic radar operations.
- **Dynamic Feedback Mechanisms:** Adapting T_{TTI} based on real-time interference, retransmissions, and user demands.
- **Multi-Objective Optimization:** Balancing collision probability, retransmissions, throughput, and fairness for a comprehensive coexistence strategy.

These extensions aim to provide a more robust framework for symbol-level TTI optimization in radar-5G coexistence scenarios.

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