Jamming-Resilient Handover Triggering for Programmable 6G Radio Access Networks using Reinforcement Learning

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- Introduction & Motivation
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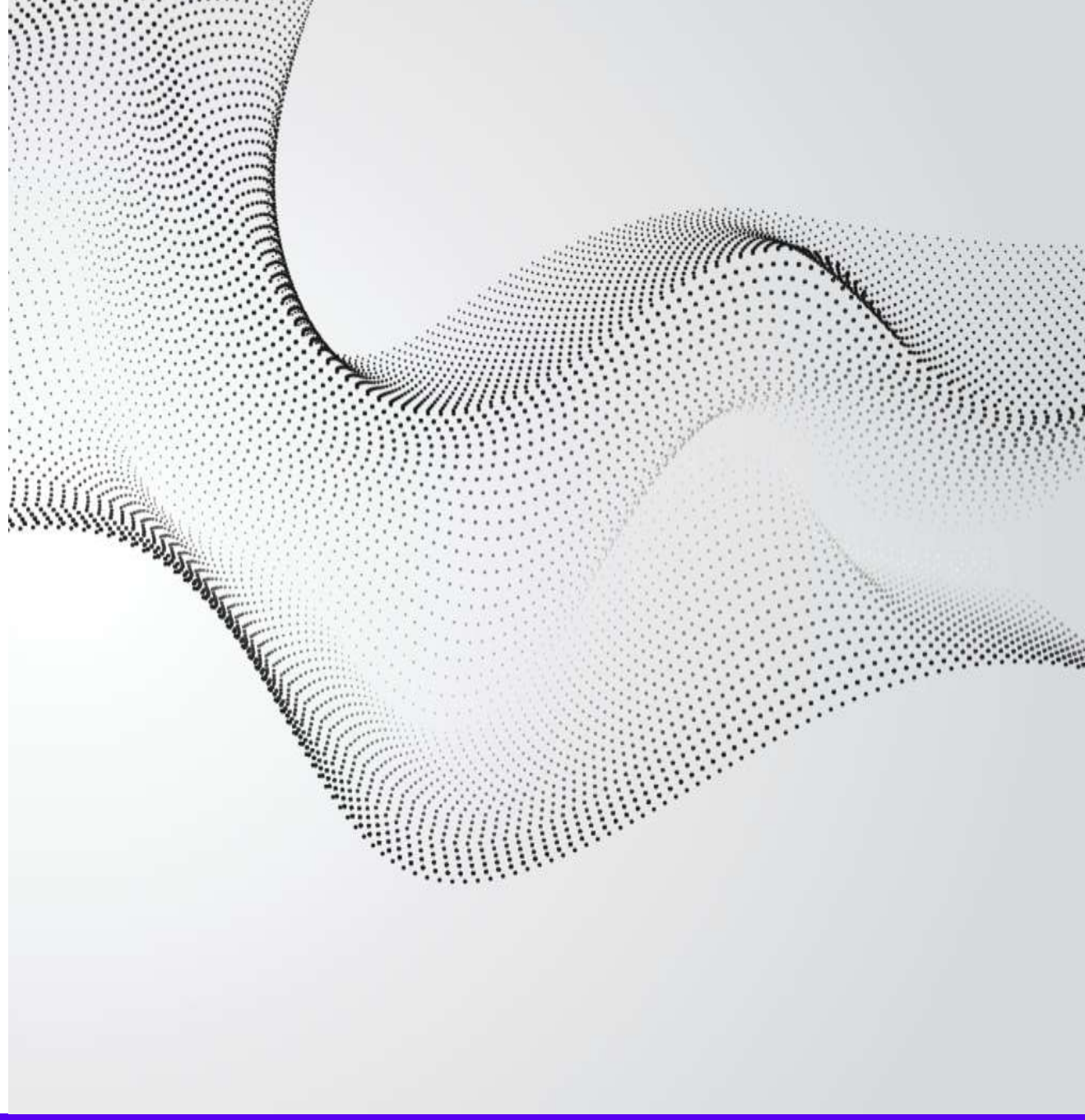


Introduction & Motivation

Resilient operation under sudden Radio Frequency disruption is critical for the next-generation cellular networks.

- Conventional **static event-trigger handover** logic creates a fatal race condition under jamming.
- Slow-moving metrics like Reference Signal Received Power (**RSRP**) arrive **too late to be decoded** successfully by a user (UE).
- The Signal to Interference Noise Ratio (**SINR**) of UE **collapses rapidly** due to jamming attack, resulting in **radio link failure**.

Issue	Impact
Jamming attack + static event-trigger handover	Fatal race condition under jamming
RSSP metric arrives too late to be decoded	SINR of a UE decreases quickly and radio link is terminated

Contribution

The basic contribution of this paper can be summarized through the following bullet points:

- RL-based policy that **replaces the traditional fixed threshold rule for handovers** between a serving and an adjacent base station.
- The RL agent is encapsulated as an **O-RAN near-real-time xApp** and examines a reduced state vector for learning the signs of a jamming attack and **proactively completing the handover** action.
- The **3GPP protocols** themselves remain **intact** in our implementation.

Background: 5G/6G terminology

➢ Handovers

- In any telecom environment, base stations allow UEs to ***report the signal quality of both the serving cell and the neighbor cells*** using multiple metrics like RSRP and SINR.
- A handover between two cells is conducted, where an ***A3 event*** occurs.
- According to 3GPP specifications, an A3 event occurs, when the ***neighbor cell becomes offset better than the serving cell for a preconfigured Time-To-Trigger (TTT) interval***.
- This is an "intrinsic vulnerability" of 3GPP design regarding the mobility triggers, since incorrect settings (values) of offset or TTT can result in either ***ping-pong handovers or radio links failure***.

➢ RIC

- RIC stands for RAN Intelligent Controller and is a key component of O-RAN
- It ***optimizes and manages the RAN using AI, automation an programmability***, improving efficiency and performance.
- The RIC is divided into two logical components: (a) real-time RIC and (b) non-real-time RIC

Background: 5G/6G terminology

➢ Real-time RIC and xApp

- Time scale from ***10ms to 1s***.
- Runs closer to the network (***edge***) for making ***fast decisions***, such as the adjustment of beamforming parameters, the dynamic allocation of radio resources and the interference management.
- Communicates with gNB via the ***E2*** interface and with non-real-time RIC via the ***A1*** interface.
- Hosts ***xApps***, applications that are able to react rapidly to network events.

➢ Non-real-time RIC and rApp

- Time scale ***above 1s***.
- Runs on ***cloud*** or a central data server, in the Service Management and Orchestration (SMO) layer for making ***strategic decisions***, such as long-term optimization, policy enforcement and network analytics.
- Communicates with gNB via the real-time RIC via the ***A1*** interface.
- Hosts ***rApps***, applications that can optimize RAN through AI-driven insights.

Background: Reinforcement Learning and Q-Learning

➢ Reinforcement Learning (RL)

- RL is a distinct ***branch of ML***, where an ***agent*** learns to make decisions by interacting with its environment in order to maximize a ***reward function***.
- We can imagine reward function as a signal that ***quantifies how good or bad an action/outcome*** is expected to be.
- The overall concept is similar to a ***feedback loop system***, since the agent acts inside an environment, the environments responds with a reward, the agent updates its strategy and finally, it learns how to act in each state.

➢ Q-Learning

- Q-Learning is a ***specific RL algorithm***, where the agent learns the Quality of (state-action) pairs using a Q-table.
- A Q-table stores entries corresponding to each ***(state, action) pair*** and contains an ***estimation of a long-term reward.***
- Over time, the values of the Q-table ***converge to their optimal*** value, so now the agent is able to take the proper action when it is found in a current state, by knowing the ***expected reward***, found in the Q-table.

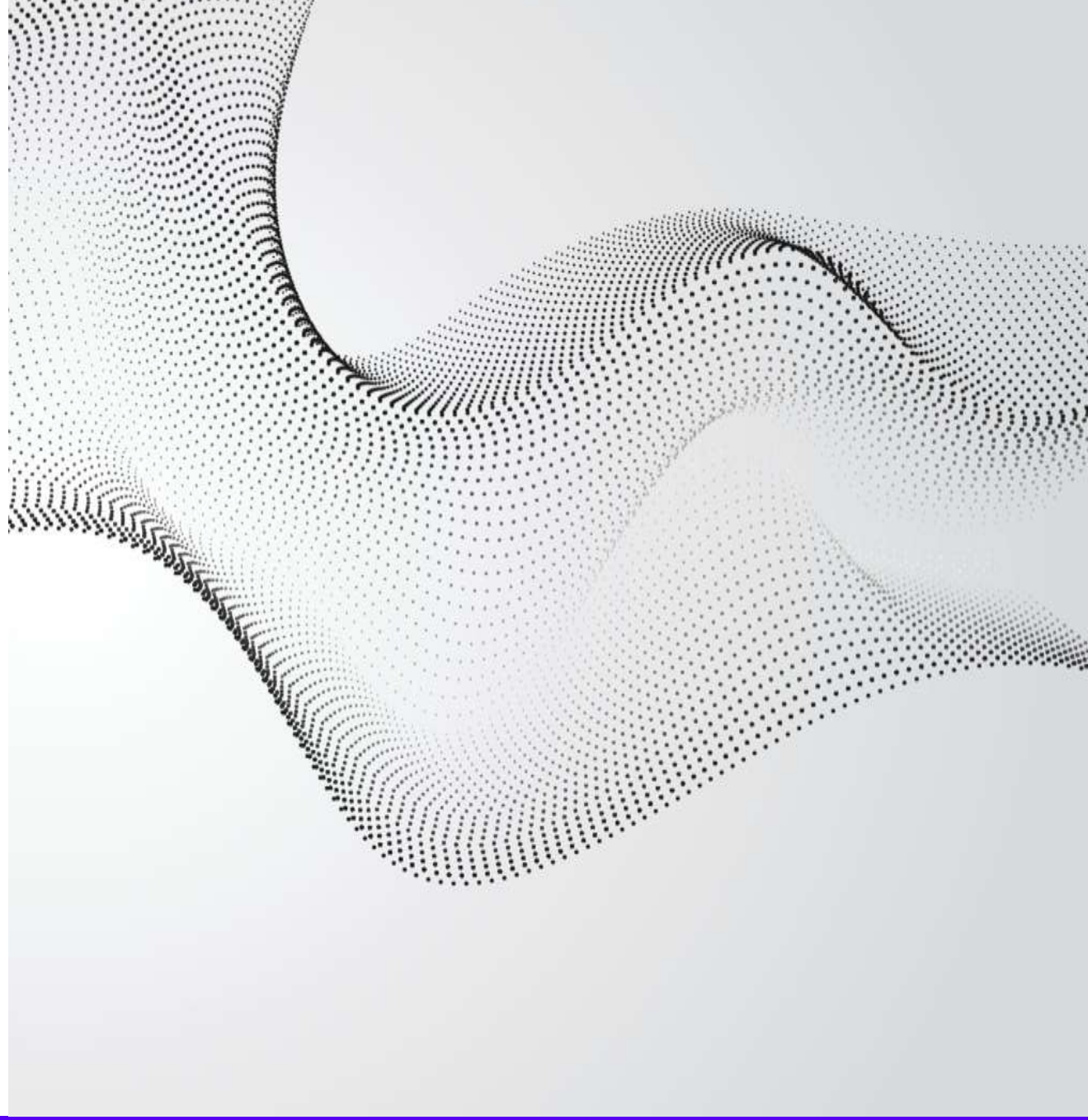
The proposed RL-based policy mechanism

❑ The problem

- Reactive ***jammers can collapse the SINR*** of a serving link within a few milliseconds, before any recovery action is completed.
- No handover takes place during this time frame, since the RSSP metric arrives too late.
- The ***serving link becomes unusable*** and even if there are any operational neighbor cells, the communication is terminated.

❑ The solution

- A lightweight, ***RL-based agent*** that interprets real-time KPIs to issue traditional handover commands or dynamic updates to UE's cluster.



The proposed RL-based policy mechanism

➢ RL-based agent vs RIC vs 6G

- RIC can host AI-driven defense mechanisms that react to PHY layer threats in just a few milliseconds.
- The RL-based agent can be implemented in ***Python and represents a RIC-hosted xApp*** that responds to jamming-induced handover triggers.
- This is in accordance to 6G's vision of zero-trust and self-defending networks.

➢ Agent's contribution

- Replaces the traditional static rule with a ***proactive, security-oriented policy***.
- *How? It* ***triggers handovers preemptively*** within the critical time window, when the radio link is still alive and the network can ***successfully deliver the handover command***.

Architecture framework

➢ The overall architecture

In order to respond to wideband jammers and trigger handovers proactively when needed, we define the following functional prototype architecture:

1. Python RL-based = xApp
2. TCP socket = E2 interface between xApp and gNB
3. C++ hook = E2 agent

➢ The agent's architecture

The agent builds a reduced state vector s, which is essentially a three-tuple with discretized components.

$$s = \{SINR_{bin}, \Delta SSR_{bin}, NACK_{bin}\}$$

Where:

1. $\boldsymbol{SINR_{bin}}$: the discretized $SINR$
2. $\boldsymbol{\Delta RSRP_{bin}}$: the RSRP difference between the serving and the neighbor gNB
3. $\boldsymbol{NACK_{bin}}$: the density of HARQ NACKs (NACK means that the receiver detected errors in the received data and requests a retransmission)

Architecture framework

Since there are 3 possible values for discretized SINR, 2 for serving-to-neighbor difference and 3 for HARQ NACK density, it is understood that there are ***18 possible states***.

The three metrics serve as ***recognizable KPIs that indicate if the agent should trigger a proactive handover***. In any case, since the agent will either trigger a handover or not, the action space is minimal and defined as:

$$A = \{defer, trigger\}$$

Regarding the reward signal r of the reward function, we can see the right-side matrix for the ***values mapping***.

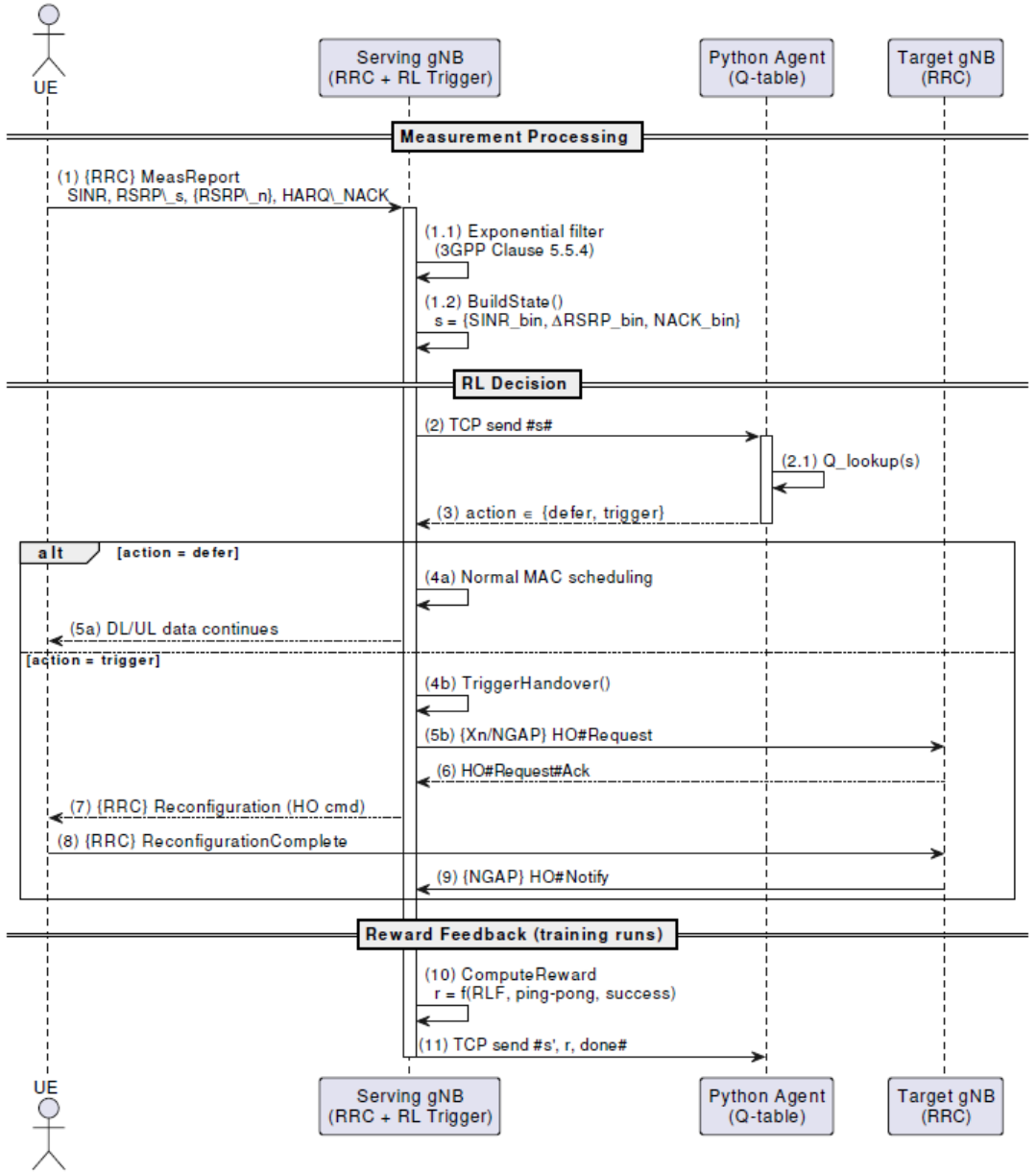
Metric	Level	Meaning
$SINR_{bin}$	Low	< 0 dB
	Medium	0 – 10 dB
	High	> 10 dB
ΔSSR_{bin}	Negative	Serving cell is stronger
	Positive	Neighbor cell is stronger
$NACK_{bin}$	Low	< 10%
	Medium	10% – 40%
	High	> 40%

Value r	Impact	Meaning
-10	Radio Link Failure	Large penalty: connectivity lost
-5	Ping-pong HO	Moderate penalty: instable network
+1	Healthy defer action	Small reward: Discourage unnecessary HOs
+10	Successful stable HO	Small reward: Proactive HO

Sequence Diagram

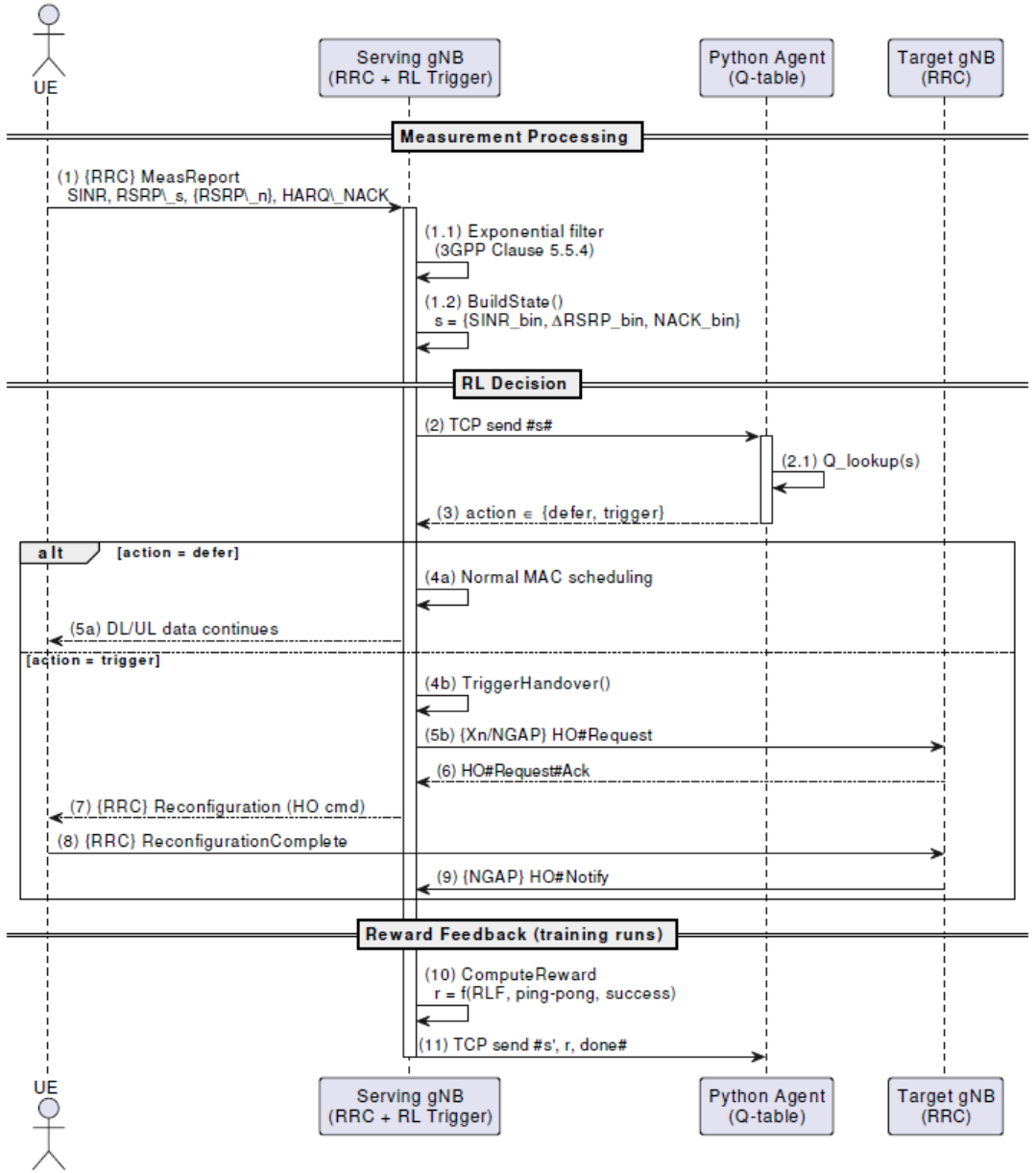
In the diagram, there are ***4 actors***: (a) the UE, (b) the serving gNB, (c) the Python agent which uses the Q-table and (d) the target gNB.

1. The serving gNB receives one of the $RRC\_MeasReport$ periodic messages from the connected UE. The message contains the values of $RSRP$ and $SINR$ and the ***C++ hook intercepts the report and build the state vector s***.
2. Through a TCP socket, the vector s is ***sent to the Python agent***.
3. The agent uses its ***Q-table to perform a lookup*** on the received state and responds back to serving gNB with its action *($defer$* or *trigger)*
4. If *action == defer*, gNB continues with normal MAC scheduling.



Sequence Diagram

4. If *action == trigger*, the standard **3GPP handover** procedure will take place.
5. A *Xn/NGAP* ***HO request*** is sent from serving gNB to the target gNB via the Xn/NGAP interface.
6. The target gNB responds with a *Xn/NGAP* ***HO request ACK***.
7. The serving gNB uses the RRC protocol to issue an ***RRC Reconfiguration*** command towards the UE.
8. Finally, the **handover is completed** and an *RRC Reconfiguration Complete* message is sent from UE to the target gNB.
9. The serving gNB **gets notified** for the successful handover event with an *NGAP HO Notify* message originating from target gNB.
10. The serving gNB ***observes the action's outcome*** (e.g., successful HO, ping-pong event, radio link failure) and ***computes the reward r***.
11. The serving gNB ***sends the reward r and new the state vector s'*** back to the Python agent, which then updates its Q-table.



Implementation & Evaluation

In the following diagrams, two baselines will be used for comparison to our proposed framework:

1. **Optimized Static A3**: An exhaustive sweep over A3-Event's *offset = {0,1,2,3,4,5,6} dB* and *TTT = {0,1,…,320} ms* – selected the combination that minimizes handover failures under the specific wideband noise profile.
2. **Reactive Power Ramping:** Upon a rapid SINR drop, the UE increases its transmission power by 3 dB for 200 ms as a mitigation action against jamming.

➢ **Setup options**

- ❑ NS3-based simulation with NR/LENA component
- ❑ 4 gNBs at the 4 corners of a 1km-length rectangle
- ❑ A wideband jammer in the center of the rectangle, producing Gaussian noise
- ❑ RL: 1000 episodes and 6o seconds per episode
- ❑ Learning rate: $\alpha = 0.1$
- ❑ Discount factor: $\gamma = 0.9$
- ❑ Exploration range: *0.05 to 0.50*

Implementation & Evaluation

Figure 1: $\boldsymbol{P(HO_{fail}) = f(P_{noise})}$

- As the noise power increases, the number of failed handovers also increases for all schemes, as expected.
- However, the RL agent approach is far more robust, as it demonstrates great resilience, even under high-power noise injection ($40dbm = 10\ Watts$).

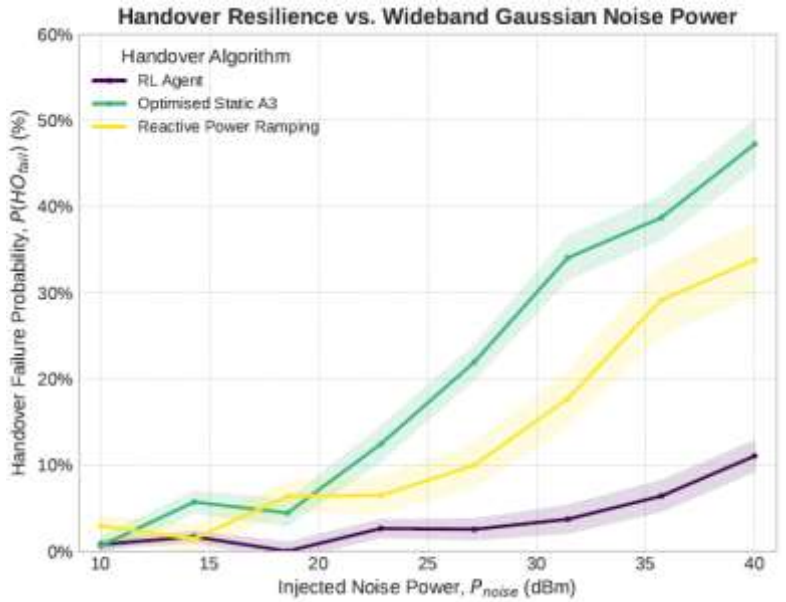
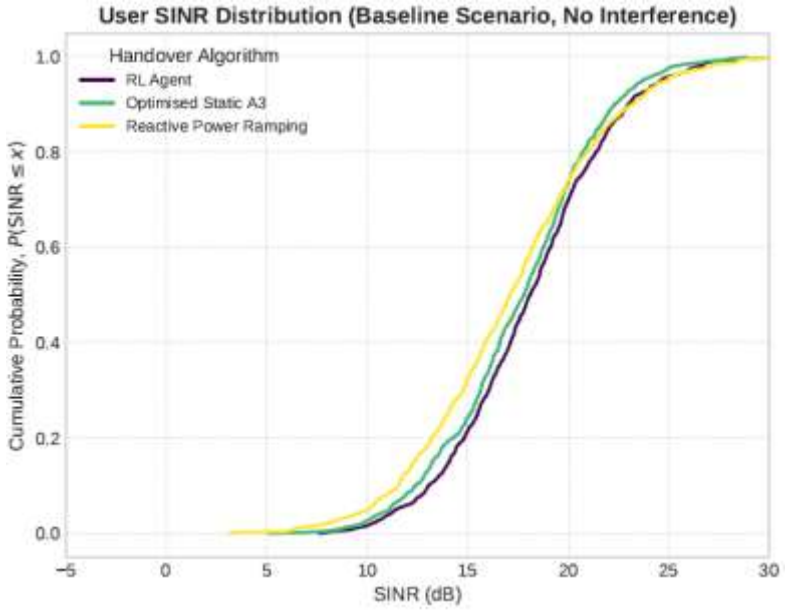


Figure 2: $\boldsymbol{CDF}$ **of** $\boldsymbol{SINR}$ **(noise only)**

- The Cumulative Density Function (CDF) of SINR has almost identical shape, regardless the deployed algorithm, in no-interference scenario.
- The RL agent does not affect the system in a clean channel environment, since all algorithms maintain a high SINR distribution.



Implementation & Evaluation

Figure 3: CDF of $SINR$ (noise + interference)

- In this case, wideband Gaussian noise has been added, so the jammer acts as an interference source.
- The RL agent proactively triggers handovers and maintains a healthier radio link for the connected UE, keeping the SINR in a range, where control commands can be successfully decoded.

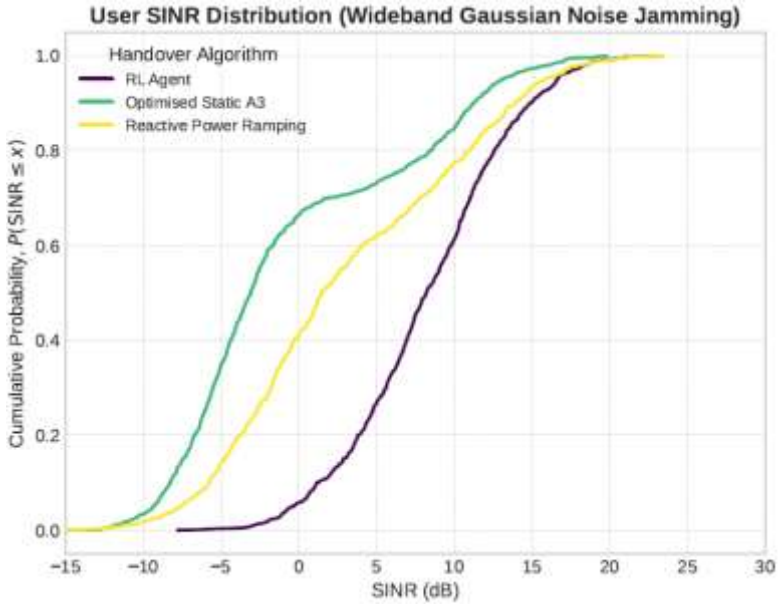
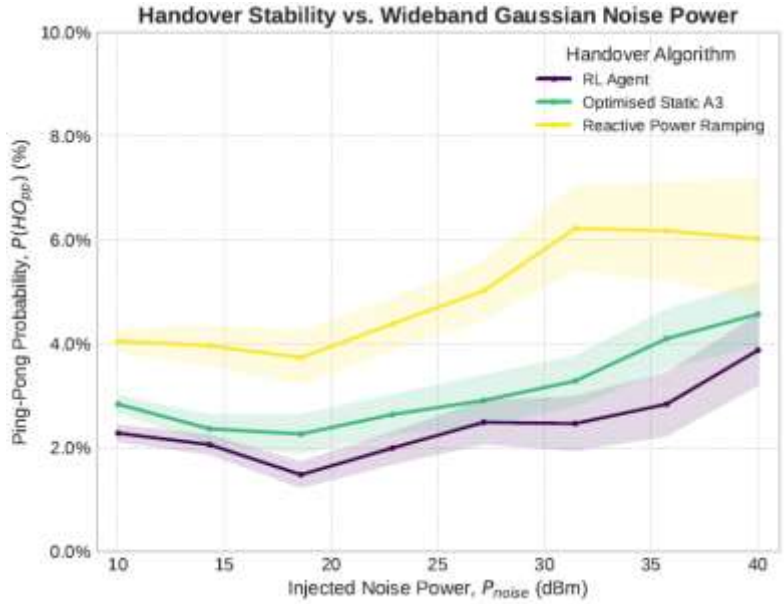


Figure 4: $P(HO_{ping-pong}) = f(P_{noise})$

- As the noise power increases, the number of ping-pong handovers typically increases for all schemes.
- Around the 15-20 dBm area, all schemes demonstrate a dip, showing a decision-freezing effect.
- However, the RL agent is again resilient without any substantial trade-off, since its stability degrades in a graceful manner, staying within the acceptable limits.



Conclusion & Future Work

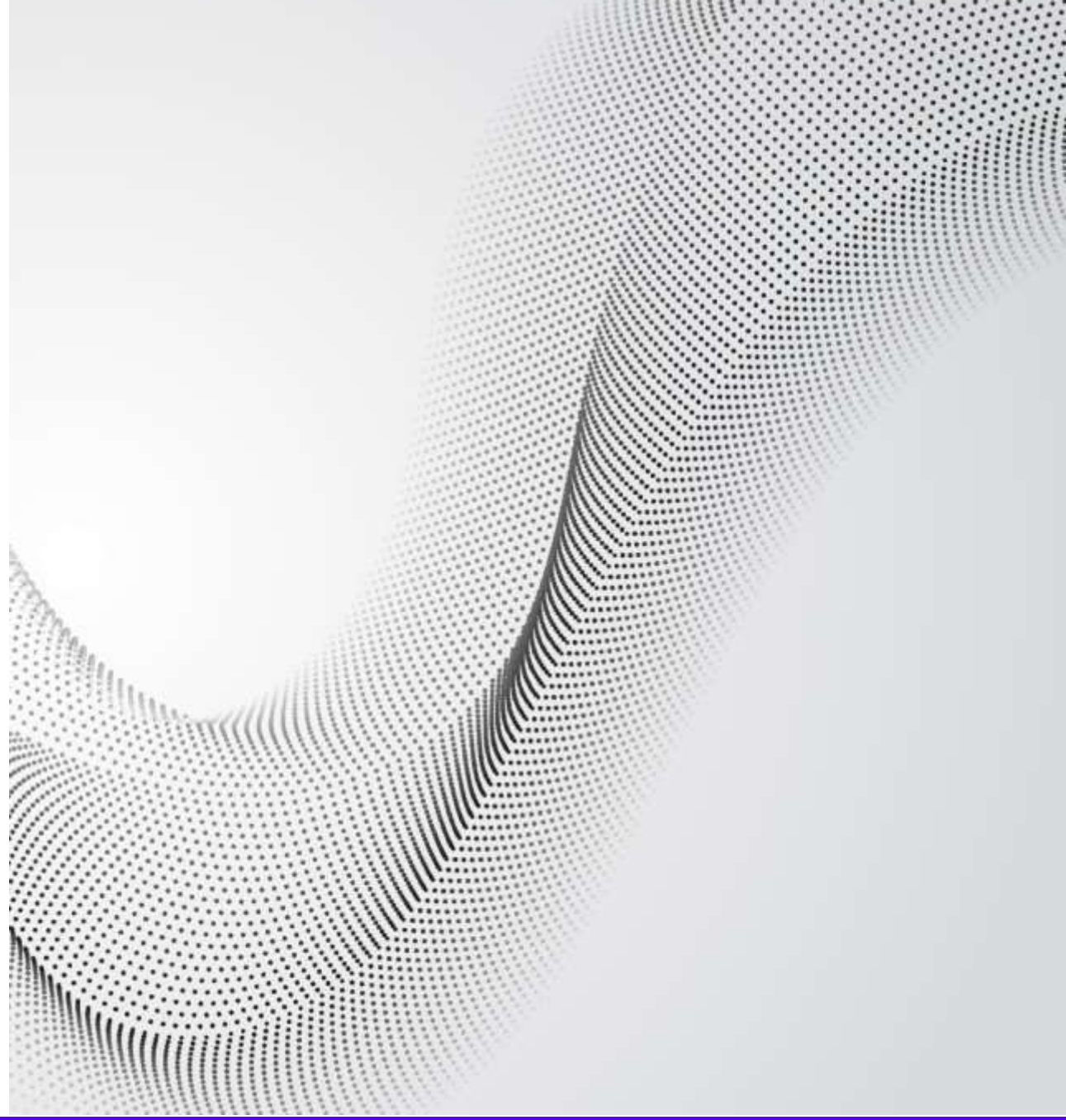
➢ Conclusion

- We replace the static 3GPP rule for handover command with a Python-based RL agent that enforces proactive policy and offers resilience and network stability.
- The agent learns to treat rapid instantaneous SINR drops and HARQ NACKs density as indicators of a potential radio link failure, before the link degrades → initiates preemptively a handover
- The agent also learns that there is a penalty for unnecessary handovers (ping-pong effect), so that it proceeds in such an option, only when a viable gNB exists.
- The system's design is an analogue to the RIC paradigm, since the Python script serves as the xApp, the TCP socket as the E2 interface and the C++ hook as the agent in E2 interface.

➢ Future Work

- The agent's state vector can be extended to include user's velocity for high mobility scenarios, cell-load metrics for network congestion scenarios, even trust scores and authentication flags for security-oriented applications.
- Scaling of the current solution, by replacing the Q-agent with a Deep Q-Network for multi-user and multi-gNB environments.

Thank you



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