Cognitive Anti-jamming Satellite-to-Ground Communications on NASA's SCaN Testbed

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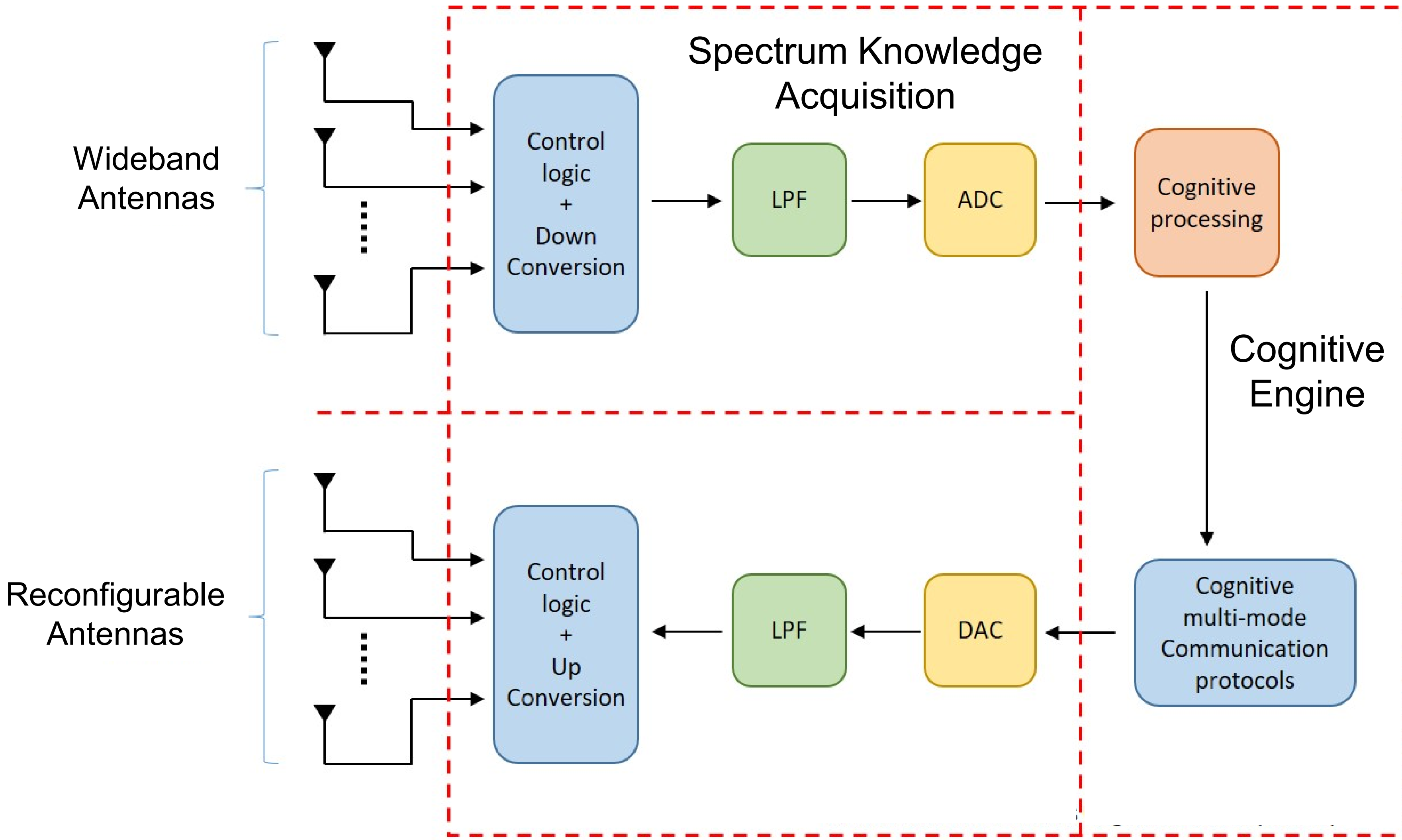
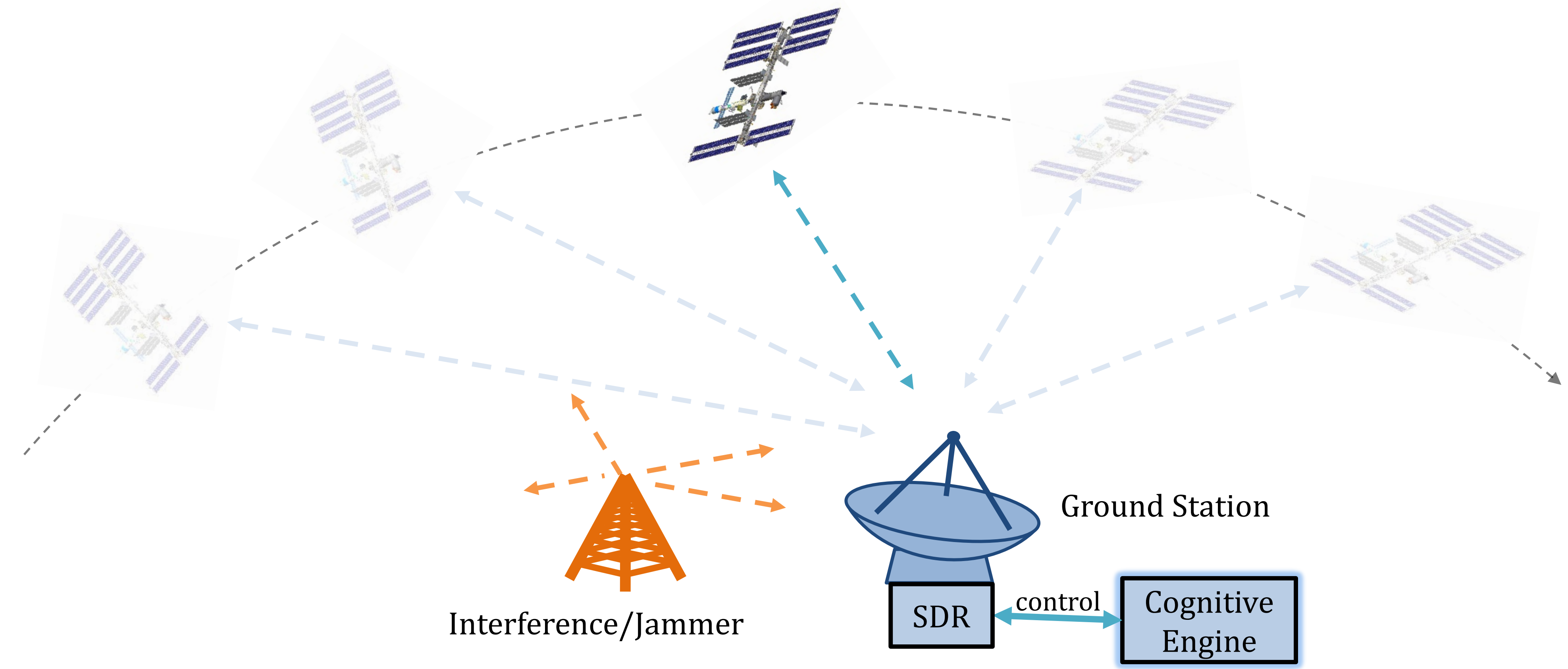
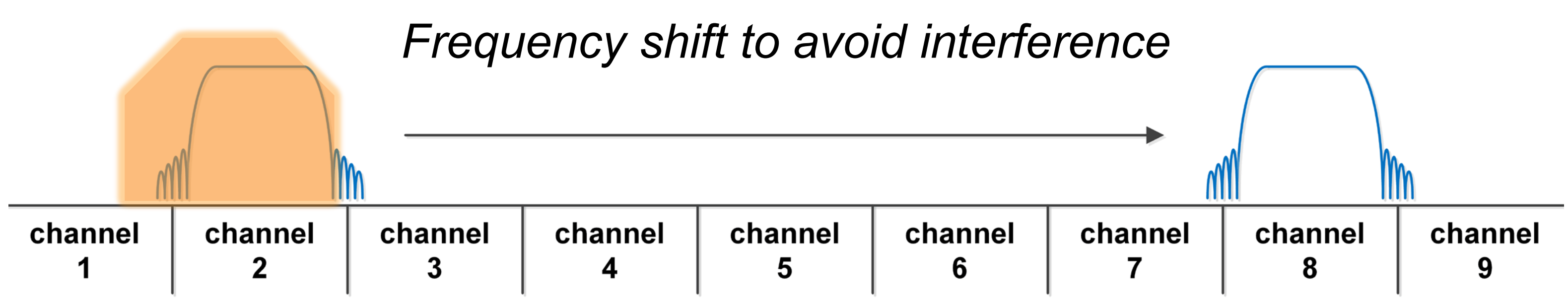
Wideband Autonomous Cognitive Radio(WARC) Architecture

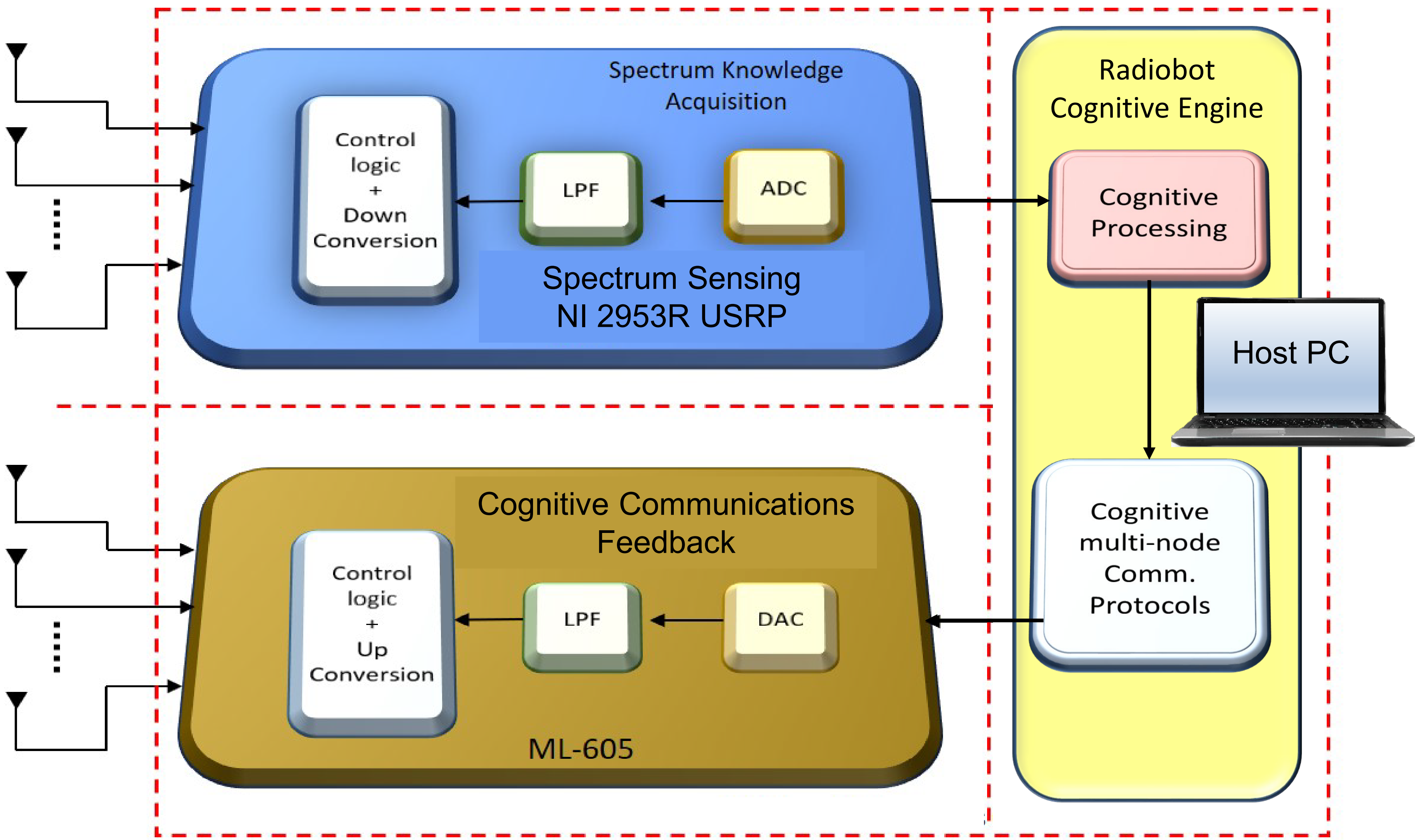


Satellite-to-Ground Cognitive Anti-Jamming (CAJ) Communications: Concept of Operations





Implemented WACR System



WARC operation with two separate SDR modules instead of a single SDR module.

Radiobot Cognitive Engine: CAJ Policy Options

1. Load a pre-learned policy from a file and keep updating the policy during the communications phase.

2. Learn a policy during a training period and keep updating the policy during the communications phase.

3. Learn a policy during a training period and keep it fixed during the communications phase.

CAJ Policy with Reinforcement Learning: Watkin's Q-Learning Algorithm

$$Q(s,a) = (1-\alpha)Q(s,a) + \alpha\left(r + \gamma \max_{a'} Q(a,a')\right)$$

NOTE: Learning rate (α) and Forgetting factor (γ) both held constant for this experiment.

Exploration vs Exploitation

$$\pi_t(s) = arg \max_a Q_t(s, a)$$

$$a_t(s) = \begin{cases} \pi_t(s) & with\, probability \quad 1 - \varepsilon \\ U(A \backslash \{s\}) & with\, probability \quad \varepsilon \end{cases}$$

- Learned policies can be used with an exploration rate (ε) during the communications phase.
  - Allows discovery of possible new optimal (state, action) pairs.
  - Must be balanced with exploitation of the already learned policy.
- Complete exploitation of previously learned policy is obtained setting ε to zero.

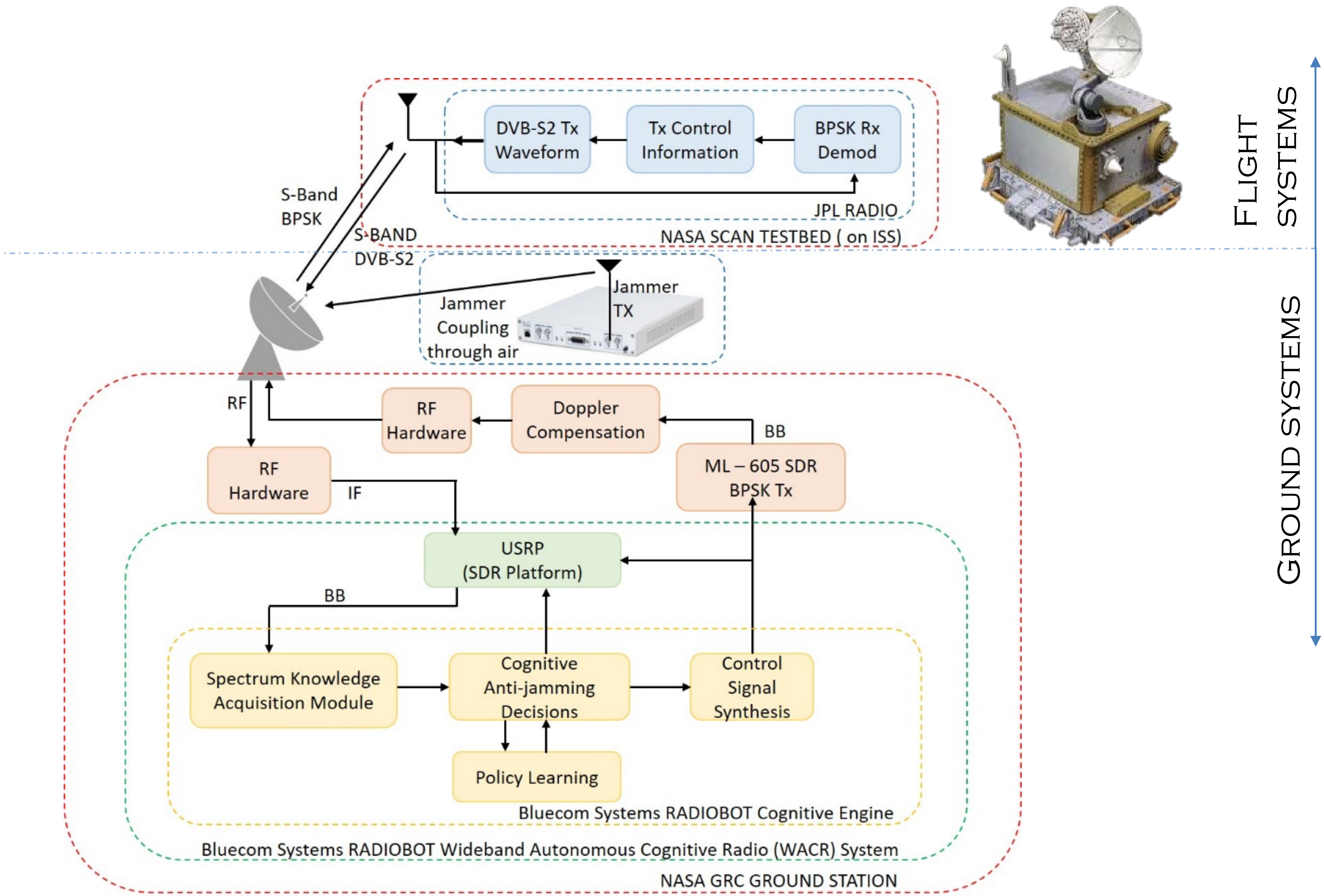
CAJ with a Random Policy

- Set the exploration rate to unity during communications phase to achieve a random channel selection policy.

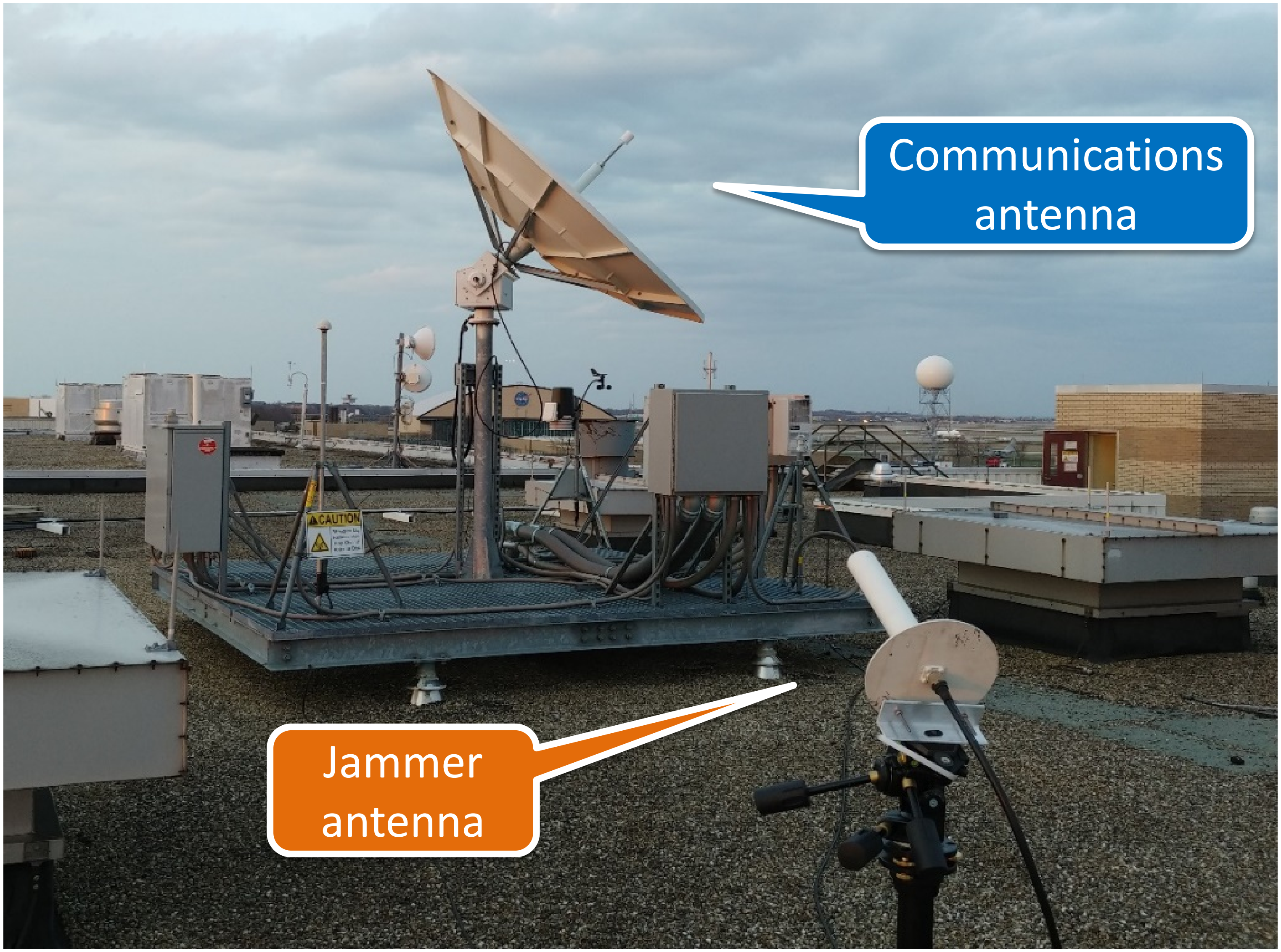
- Random channel selection policy does not mean it is a traditional radio.
  - Even when the policy is to select channels randomly, the radio is still a WACR.

- Random policy is used to evaluate the effectiveness of the learning process, not the effectiveness of cognitive communications.
  - To perform anti-jamming communications, even with a random policy, the radio still needs the spectrum knowledge of the cognitive radio.
  - Hence, it is still autonomously mitigating the jammer.

Flight Testing System Configuration

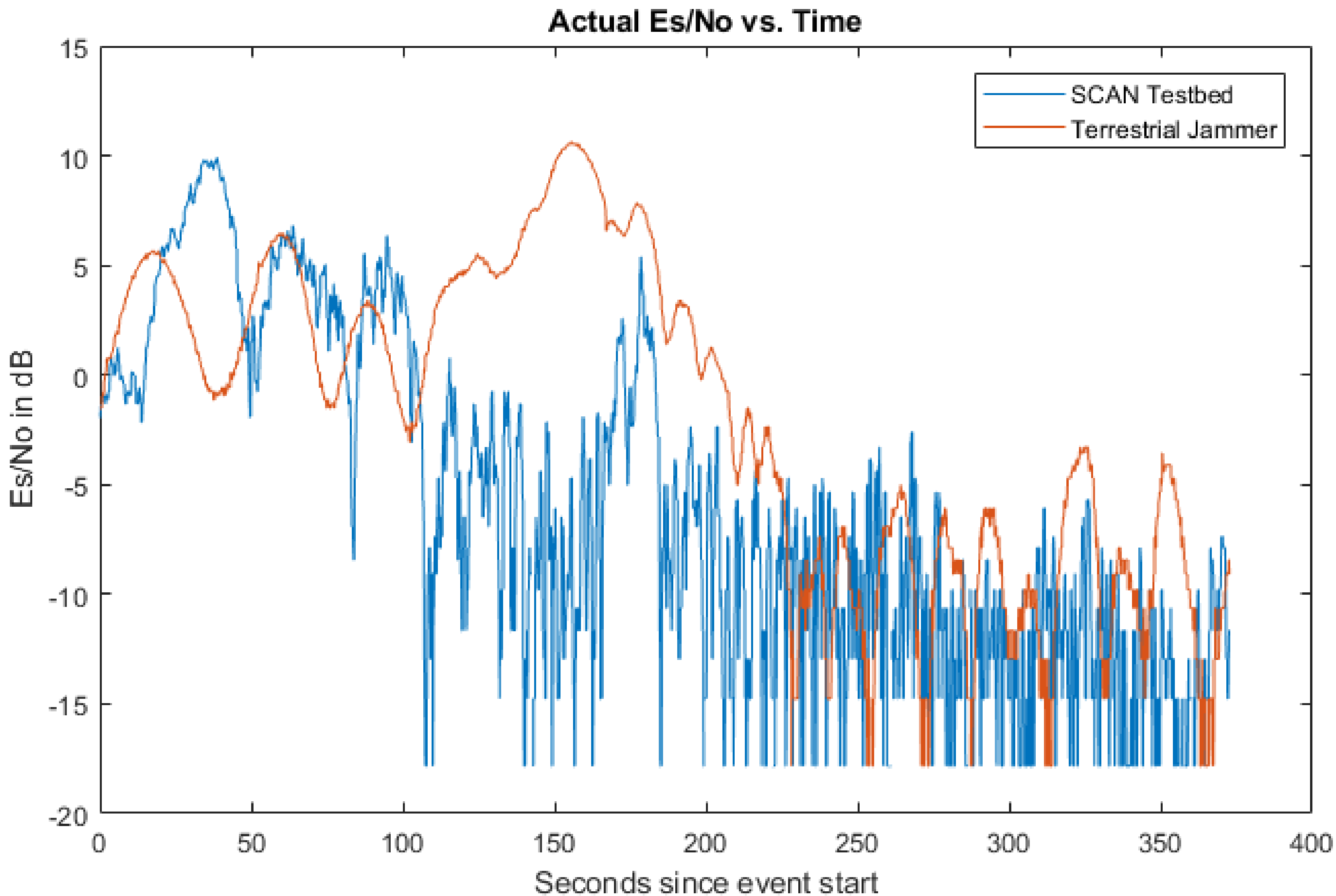


Flight Testing
Ground Station Antenna Setup



Over-the-air jammer antenna setup on same rooftop as main ground station.

Flight Testing: Relative Powers of Satellite and Jammer Signals



Flight Testing Event Data

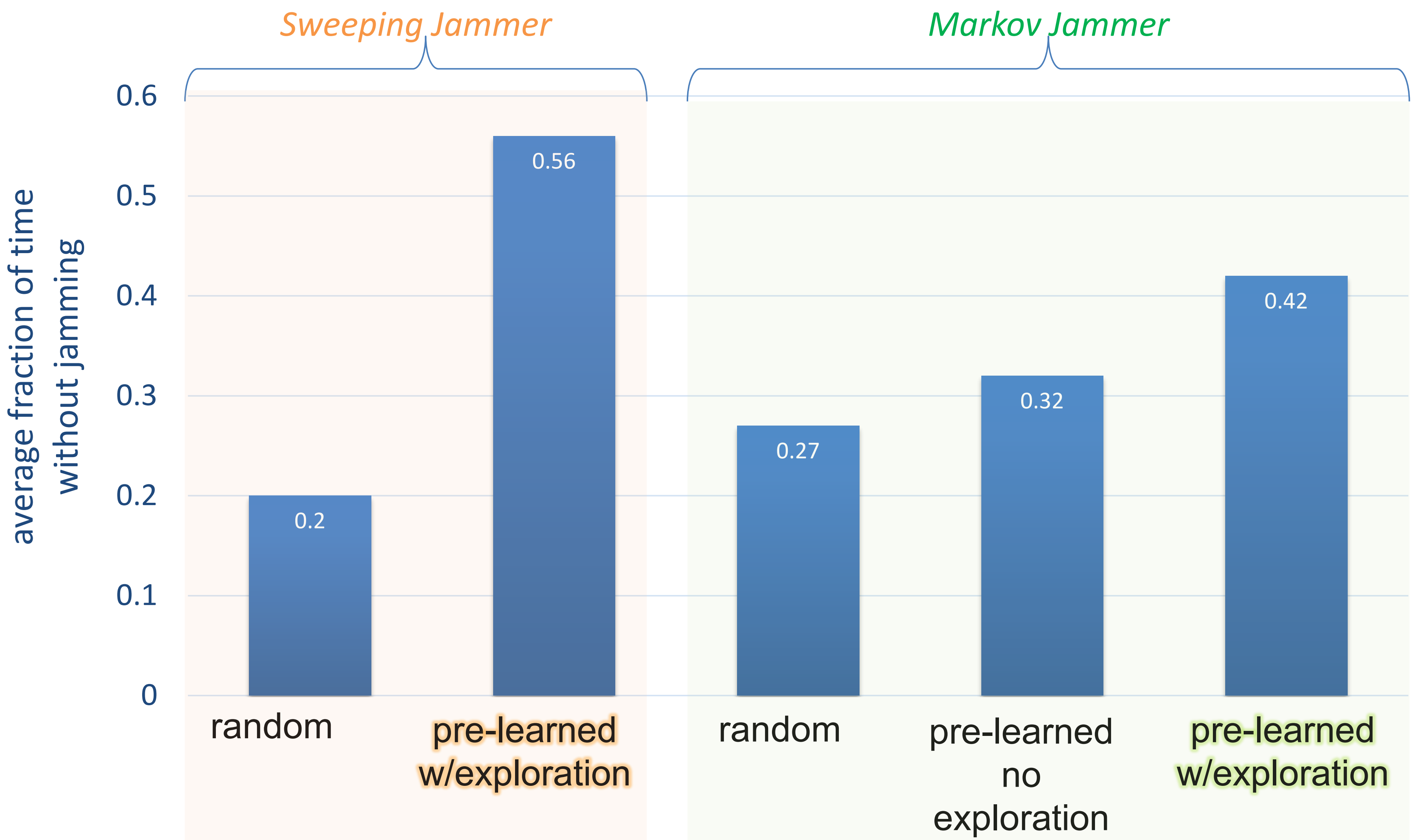
Test #	Jammer Type	Policy Type	Exploration Rate (ε)	Total Number of Sensing Periods During the Complete Event-pass	Total Number of Sensing Periods with Sufficient Signal Quality Between Channel Transitions	Number of Channel Transitions
1	sweep	random	1.0	214710	29380	21
2	sweep	random	1.0	218545	96337	77
3	sweep	pre-learned	0.3	235192	132380	81
4	sweep	pre-learned	0.3	120370	298	4
5	Markov	random	1.0	192751	51412	67
6	Markov	pre-learned	0.0	229520	72908	79
7	Markov	pre-learned	0.3	266661	112660	115

Learning rate (α) set to 0.3, and Forgetting factor (γ) set to 0.8 for all tests.

Flight Testing: Performance Evaluation of CAJ Communications

Test #	Jammer type	Policy Type	Exploration Rate (ε)	Average time in a Channel Without Being Jammed	Average Fraction of time in a Channel Without Being Jammed
1	Sweep	Random	1.0	1399	0.14
2	Sweep	Random	1.0	1251	0.44
1 & 2	Sweep	Random	1.0	1325	0.20
3	Sweep	Pre-learned, continuously updated through exploration	0.3	1634	0.56
5	Markov	Random	1.0	767	0.27
6	Markov	Pre-learned and fixed.	0.0	922	0.32
7	Markov	Pre-learned, continuously updated through exploration	0.3	980	0.42

Flight Testing:
Policy vs Random Performance



Conclusions

- Results show that the developed WACR approach is an effective anti-jamming tool, regardless of learning type and channel selection algorithms are used.

- Reinforcement learning aided cognitive anti-jamming communications policy significantly outperforms the random channel selection policy, both in terms of the average unjammed time in a channel as well as the fraction of time in a channel without being jammed.

- Performance is consistent regardless of the type of the jammer: Sweep or Markov.

- Allowing learning-based policy update and policy exploration during actual RF environment will lead to better performance with cognitive anti-jamming communications.

- Best possible performance improvements with the CAJ communications policy can expected to be higher than what is observed in these tests since these tests only allowed a very short learning period length, and parameters of the algorithms (i.e. learning rate, and forgetting factor, etc.) were unoptimized arbitrary values.

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