6GAN: IPv6 Multi-Pattern Target Generation via Generative Adversarial Nets with Reinforcement Learning

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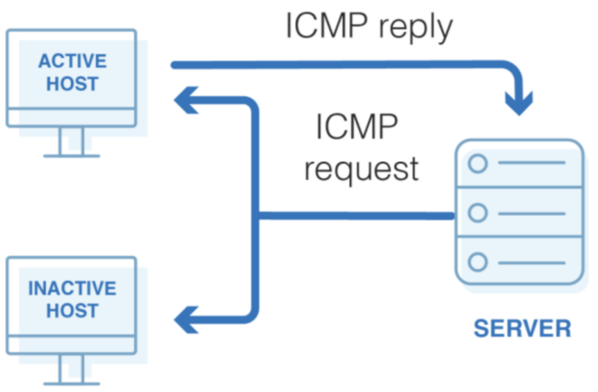
Background - IPv6 Scanning

IPv6 Scanning

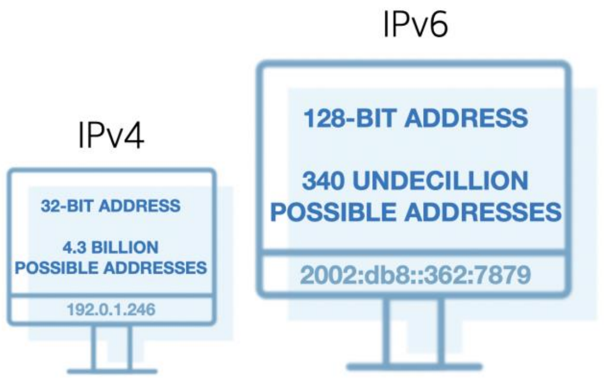
Global IPv6 Address Exploration

- Enhancing the ability of researchers to conduct wide-ranging assessments of the next-generation Internet.
- Passive measurement - limited by vantage points to monitor the traffic.
- **Active scanning** - a fast means required by the community.



Bottlenecks of IPv6 Scanning

- The system sends a ping to each device on the network and awaits a response.
- IPv6 - 128-bit address space - 340 undecillion addresses - Can not work !



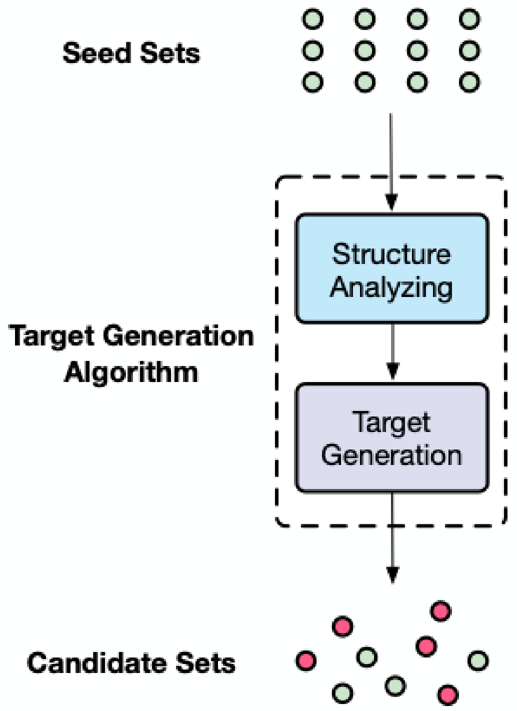
Background - IPv6 Target Generation

IPv6 Target Generation

Target Generation Algorithms[1,2,3]

- A recently proposed solution to overcome IPv6 scanning bottlenecks.
- **Seed sets** of active IPv6 seed addresses as the input.
- **Structure analyzing** - learning features of the seed set.
- **Target Generation** - predicting the active individuals or regions in the real network space to provide the **candidate set** waiting for scanning.
- Budget - the size of the candidate set.

The quality of the candidate set is directly determined by the algorithmic design.



[1] Foremski, P., Plonka, D., Berger, A.: Entropy/ip: Uncovering structure in ipv6 addresses. In: Proceedings of the 2016 Internet Measurement Conference. pp. 167–181. ACM (2016)
[2] Murdock, A., Li, F., Bramsen, P., Durumeric, Z., Paxson, V.: Target generation for internet-wide ipv6 scanning. In: Proceedings of the 2017 Internet Measurement Conference. pp. 242–253 (2017)
[3] Z. Liu, Y. Xiong, X. Liu, W. Xie, and P. Zhu, "6tree: Efficient dynamic discovery of active addresses in the ipv6 address space," Computer Networks, vol. 155, pp. 31–46, 2019.

Challenge - IPv6 Addressing Pattern

Target Generation Challenge

Challenge 1 - IPv6 addressing pattern

Network administrators are allowed to freely select IPv6 address configuration schemes, which enables multiple allocation patterns for **interface identifier (IID)** in the address. According to RFC 7707:

Embedded-IPv4	0:0:c0a8:20a	Embedding an IPv4 address 192.168.2.10
Embedded-port	0:0:0:80	Embedding a decimal port 80 for HTTP
IEEE-derived	250:56ff:fe89:49be	Inserting word "fffe" between OUI and the rest of the Ethernet address
Low-byte	0:0:0:a	Only setting the least significant bytes in one or two lowest-order
Pattern-bytes	face:b00c:0:a7	Specific addressing patterns different from the above
Randomized	7c61:2880:3148:36e1	Privacy addresses with a pseudorandom IID representation

- 2001:0db8:0106:0001:????:????:????:???? - How to determine ?
- Multiple IPv6 schemes cause difficulty in algorithmic inferences.

Challenge - IPv6 Aliasing

Target Generation Challenge

Challenge 2 - IPv6 Aliasing

Aliased addresses refer to all addresses under aliased prefixes, which unconditionally respond to scan queries but are not bound to unique devices. For instance:

2001:db8::/32 is a known aliased prefix.
Then 2001:db8::20:1a is an aliased address.

- Aliased addresses seriously affect the accuracy of host discovery approaches.
- Performing alias detection has been a consensus in IPv6 scanning.

Consideration

Multi-Pattern Target Generation

- Addressing patterns could be clustered into limited categories.
- Target generation can't bear the pressure of the whole IPv6 address space.
- A deep eye on each addressing pattern are urgently required.

Algorithm-level Alias Detection

- Candidate sets detection - consuming the budget to generate aliased addresses.
- Seed sets detection - reconstructing the aliased address during prediction.
- Discouraging learning aliased prefixes during algorithmic execution.

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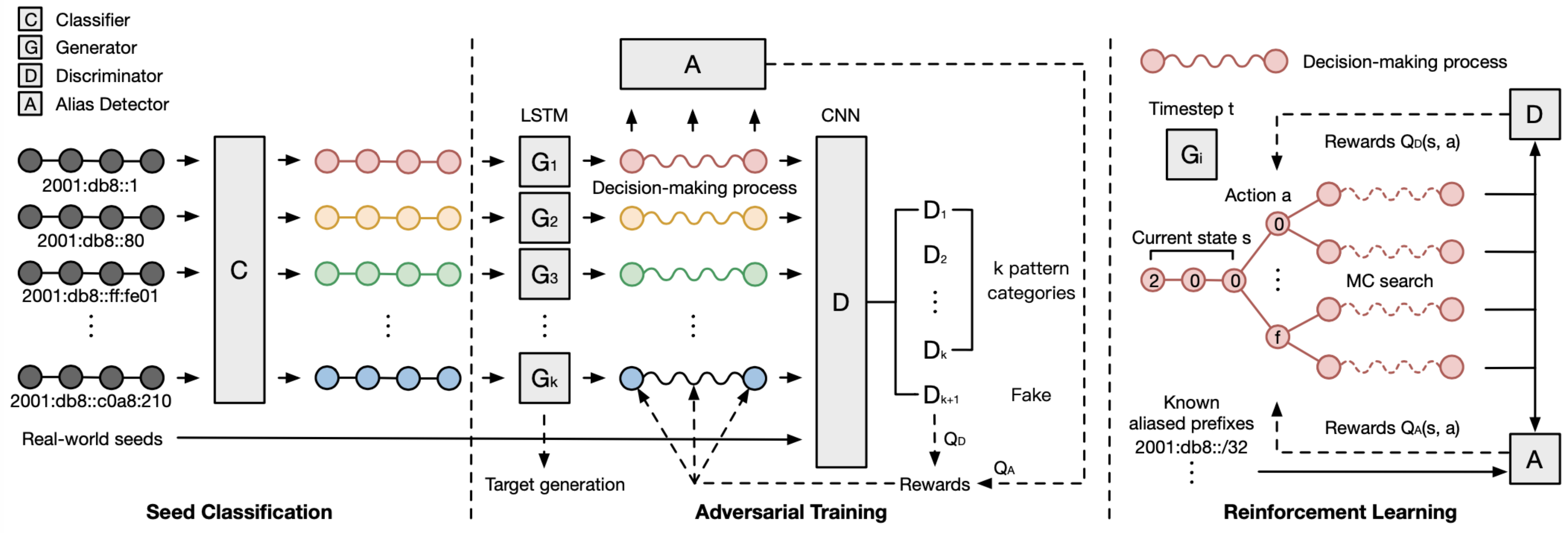
Overall Architecture



- **Seed Classification** - pattern discovery through known seed classification methods.
- **Generator Learning -** generating addresses with k pattern types to deceive the discriminator.
- **Discriminator Learning** - distinguishing between fake addresses generated by generators and real addresses.
- **Alias Detection** - helping prevent the generation of aliased addresses at the algorithmic level.

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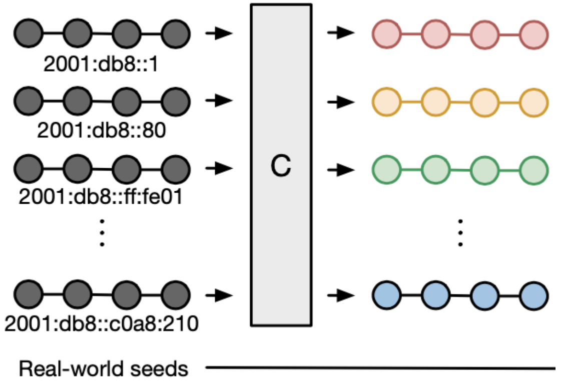
Seed Classification

we provide the following three seed classification methods to promote pattern discovery and determine the number of generators k:

- **RFC Based** - According to possible IPv6 addressing patterns proposed in RFC 7707, the addr6 tool in ipv6toolkit[4] can match the patterns mentioned in RFC 7707.

- **Entropy Clustering** - Gasser et al.[5] proposed entropy clustering, which uses information entropy of the nybble value under the same prefix in the seed set as a prefix fingerprint to perform unsupervised clustering to discover the prefix-level pattern set.

- **IPv62Vec** - Cui et al.[6] proposed IPv62Vec, which implements the mapping from address space to vector space by learning the addressing patterns with similar context of words in the address.



Seed Classification

[4] F. Gont, “Security/robustness assessment of ipv6 neighbor discovery implementations,” 2012.
[5] O. Gasser, Q. Scheitle, P. Foremski, Q. Lone, M. Korczyń ski et al., “Clusters in the expanse: Understanding and unbiasing ipv6 hitlists,” in Proceedings of the 2018 Internet Measurement Conference, IMC, 2018, pp. 364–378.
[6] T. Cui, G. Xiong, G. Gou, J. Shi, and W. Xia, “6veclm: Language modeling in vector space for ipv6 target generation,” arXiv preprint arXiv:2008.02213, 2020.

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Generator Learning

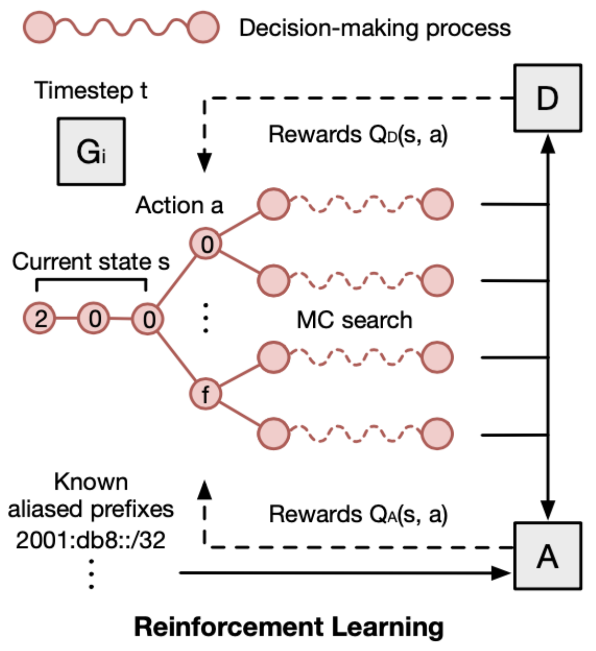
Target generation problem - address sequence decision-making problem

- A hexadecimal IPv6 address $X_{0:T} = (x_0, ..., x_t, ..., x_T), x_t \in V = \{0, 1, ..., f\}$
- State *s* at timestep *t* - currently produced address nybbles $X_{0:t-1} = (x_0, ..., x_{t-1})$
- Action *a* - the next nybble value x_t to be select
- $G_{\theta_i}(a = x_t | s = X_{0:t-1})$ - the probability of performing action *a* at the state *s*
- $Q_{AD_\phi}^{G_{\theta_i}}(s = X_{0:t-1}, a = x_t)$ - assessment of the sequence $X_{0:t}$ based on the discriminator *D* and the alias detector *A*

- The objective function $J(\theta_i)$ of the i-th generator :

$$J(\theta_i) = \sum_{t=1}^{T} G_{\theta_i}(x_t | X_{0:t-1}) Q_{AD_\phi}^{G_{\theta_i}}(X_{0:t-1}, x_t)$$

$$Q_{AD_\phi}^{G_{\theta_i}}(s, a) = Q_{D_\phi}^{G_{\theta_i}}(s, a) + \alpha Q_{A}^{G_{\theta_i}}(s, a)$$ where α is a hyperparameter.



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Generator Learning

At each timestep *t* - incomplete sequence $X_{0:t}$
To produce a complete sequence $X_{0:T}$ for judgment

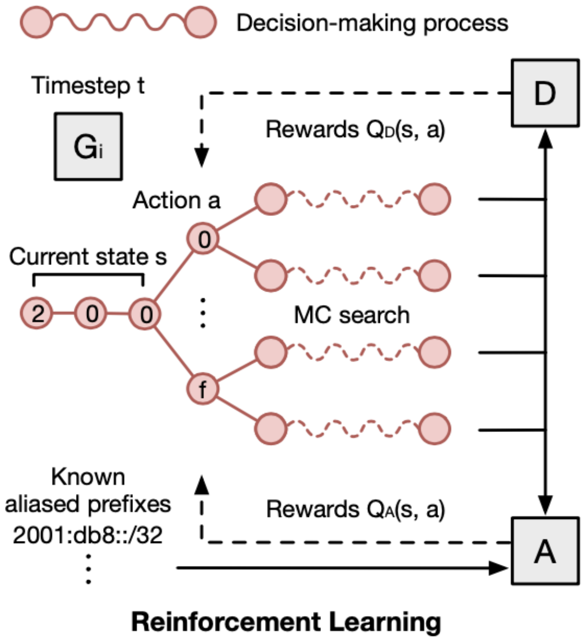
- N-time Monte Carlo search with a roll-out policy

$$\mathrm{MC}^{G_{\theta_i}}(X_{0:t}; N) = \{X_{0:T}^{1}, ..., X_{0:T}^{N}\}$$

All generators of 6GAN use Long Short-Term Memory (LSTM) cells to model $G_{\theta_i}(a|s)$:

$$p(x_t|X_{0:t-1}) = \mathrm{softmax}(c + wh_t)$$
$$\text{where} \quad h_t = \mathrm{LSTM}(h_{t-1}, x_{t-1})$$

- The parameters are a bias matrix *c* and a weight matrix *w*.
- Softmax function achieves the selection probability of x_t.
- Each generator independently learns the addressing pattern to generate specific pattern addresses.



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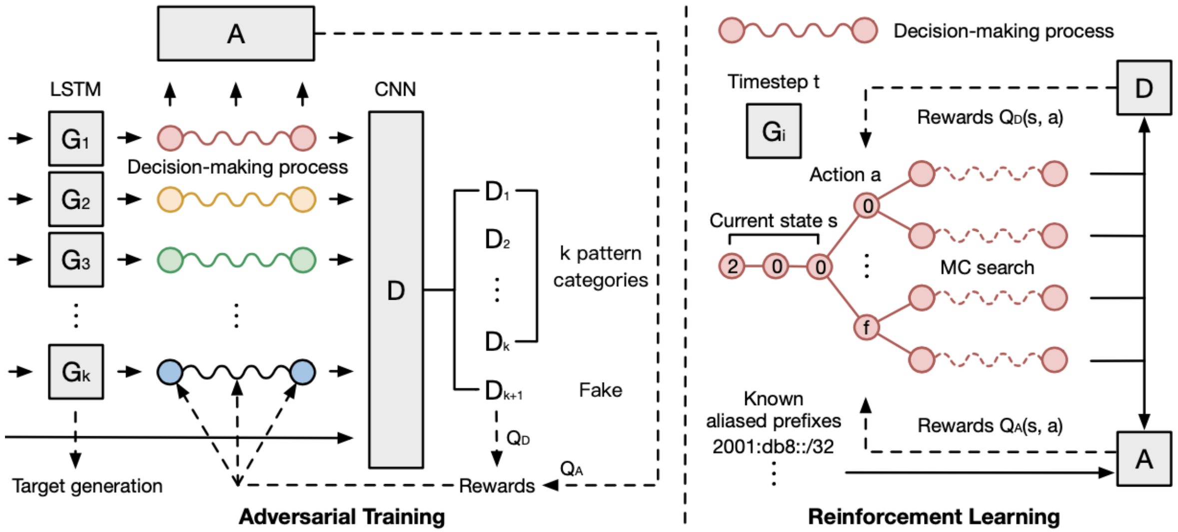
Discriminator Learning



Multi-class classification objective

- Trained with the real-world seed addresses and the generated addresses.
- k + 1 categories - k pattern categories and a fake category.
- The objective function $J(\phi)$ of the discriminator is:

$$J(\phi) = -\sum_{i=1}^{k} \mathbb{E}_{X\sim p_i}[\log D_\phi^i(X)] - \mathbb{E}_{X\sim G_\theta}[\log D_\phi^{k+1}(X)]$$

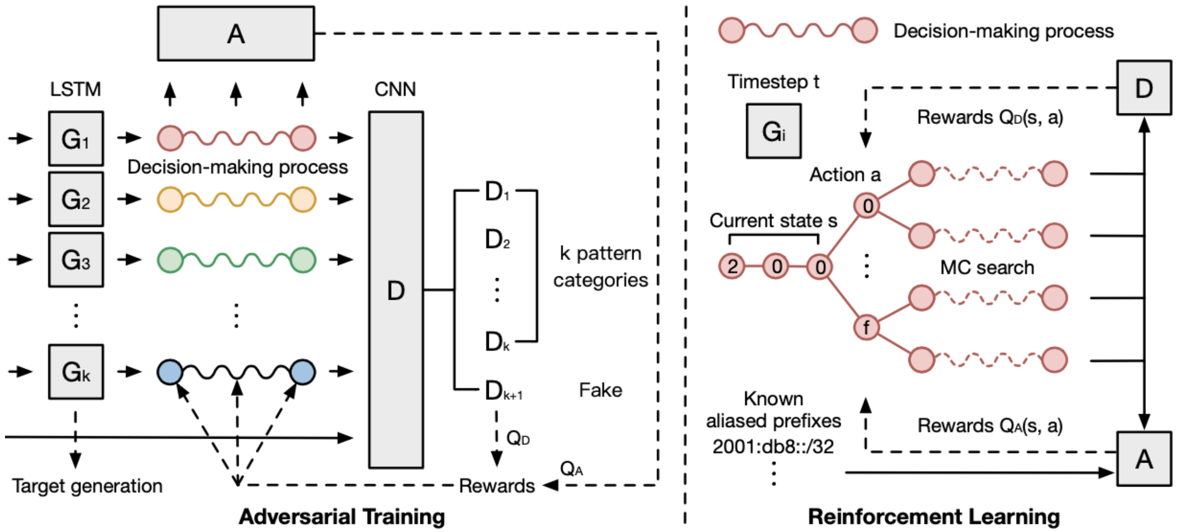
- *D(X)* scores - the probability of a sample being judged as the i-th pattern-type address.

6GAN

Discriminator Learning

- The discriminator provides the reward $Q_{D_\phi}^{G_{\theta_i}}(s, a)$

$$Q_{D_\phi}^{G_{\theta_i}}(s = X_{0:t-1}, a = x_t) = \begin{cases} \frac{1}{N}\sum_{n=1}^{N}(1 - D_\phi^i(X_{0:T}^n)), X_{0:T}^n \in \mathrm{MC}^{G_{\theta_i}}(X_{0:t}; N) & t < T \\ 1 - D_\phi^i(X_{0:t}) & t = T \end{cases}$$



- The discriminator of 6GAN is implemented using Convolutional Neural Networks (CNN) with multiple filters.

- Adversarial training - k generators and one discriminator will be trained alternately to achieve their respective goals.

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Alias Detection

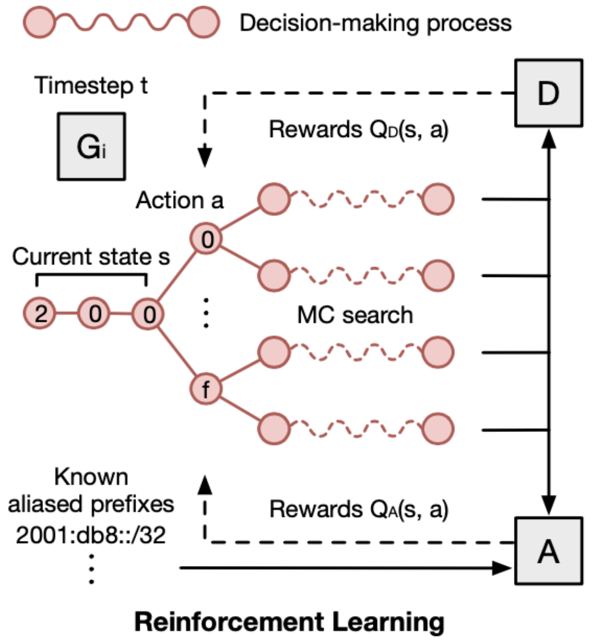
An aliased prefix $P_{0:L} = (p_0, ..., p_t, ..., p_L)$

- The alias detector provides the reward $Q_A^{G_{\theta_i}}(s, a)$
- The alias detector identifies an aliased address when $P_{0:L} = X_{0:L}$

$$A(X) = \begin{cases} \lambda & P_{0:L} = X_{0:L} \\ 0 & P_{0:L} \neq X_{0:L} \end{cases}$$

$$Q_A^{G_{\theta_i}}(s = X_{0:t-1}, a = x_t) = \begin{cases} \frac{t}{NL} \sum_{n=1}^{N} A(X_{0:T}^n), X_{0:T}^n \in \mathbf{MC}^{G_{\theta_i}}(X_{0:t}; N) & t \leq L \\ 0 & T \geq t > L \end{cases}$$

- Positive rewards are only provided on the prefix part.
- Coefficient $\frac{t}{L}$ - hierarchical rewards.
- More likely updating the high index and helping reduce the wide range changes of the prefix region.



Evaluation

Dataset and Evaluation Method

Dataset

- **IPv6 Hitlist** - Public dataset. [7]
- **CERN IPv6 2018** - Passively collected address sets under the China Education and Research Network from March to July 2018.

Dataset	Description	Period	#Seeds
IPv6 Hitlist	Active addresses	June 27, 2020	610.9k
	Source addresses		100.0k
	Aliased prefixes		516.1k
CERN IPv6 2018	Active addresses	March - July 2018	90.1k

Evaluation Method

- Zmapv6 tool. [8]
- ICMPv6, TCP/80, TCP/443, UDP/53, UDP/443 scanning.
- Continuous scanning for three days.

[7] Gasser, O., Scheitle, Q., Foremski, P., Lone, Q., Korczyn ́ski, M., Strowes, S.D., Hendriks, L., Carle, G.: Clusters in the expanse: Understanding and unbiasing ipv6 hitlists. In: Proceedings of the Internet Measurement Conference 2018. pp. 364–378. ACM (2018)
[8] IPv6 Hitlist. https://ipv6hitlist.github.io/

Evaluation

Evaluation Metric

A real-world address seed set with *k* types of pattern $S = \{S_1, ..., S_t, ..., S_k\}$.
A candidate set *C* using the *t*-th pattern generator.

- **Pattern quality** - the imitating ability of the generators to each addressing pattern.

$$Pattern(C) = \frac{1}{|C|} \sum_{i=1}^{|C|} \min\{\psi(C_i, S_{t_j})\}_{j=1}^{j=|S_t|}$$

- **Novelty quality** - the algorithmic ability to generate new address sequences.

$$Novelty(C) = \frac{e}{|C|} \sum_{i=1}^{|C|} (1 - \max\{\varphi(C_i, S_j)\}_{j=1}^{j=|S|})$$

- **Diversity quality** - whether candidate set is a diverse set, which contains a variety of se

$$Diversity(C) = \frac{e}{|C|} \sum_{i=1}^{|C|} (1 - \max\{\varphi(C_i, C_j)\}_{j=1}^{j=|C|, j \neq i})$$

- **Hit rate** - the proportion of active addresses in the candidate arning ability.

$$Hit(C) = \frac{|C \cap T - C \cap T_a|}{|C|}$$

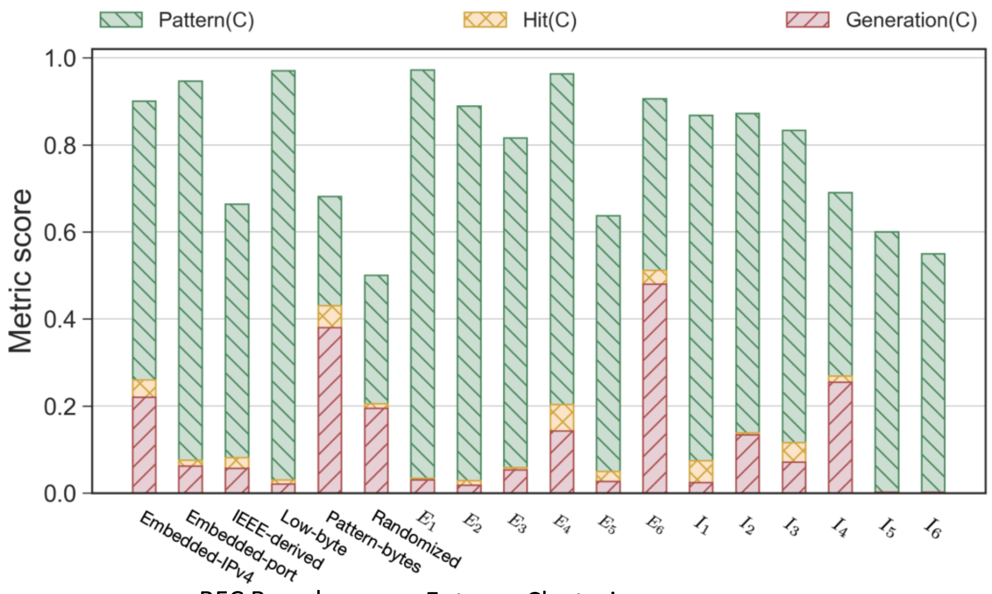
- **Generation rate** - the proportion of the active addre t in the seed ability.

$$Generation(C) = \frac{|C \cap T - C \cap T_a - C \cap S|}{|C|}$$

Where ψ is the Cosine similarity function, φ is the Jaccard similarity function, *e* = 100, *T* is the real active target set in the IPv6 space and T_a is the real aliased addresses set.

Evaluation

Pattern Target Generation



Seed Classification	Budget Allocation	#Targets	Generation(C)
None	1	0.5k	1.06%
RFC Based	11:3:3:1:19:10	12.7k	25.43%
Entropy Clustering	2:1:3:8:1:26	16.9k	33.82%
IPv62Vec	13:70:40:141:1:1	9.1k	18.19%

3 metric scores on each pattern

- 6GAN has a strong ability to imitate most patterns.
- Generation rate - the active user distribution in the addressing patterns.

6GAN's budget allocation

Given the generation rates of k patterns $(r_1, ..., r_i, ..., r_k)$ and the total budget $|C|$.

- the allocated budget of i-th pattern $|C_i|$:

$$|C_i| = \frac{r_i}{\sum_{j=1}^{k} r_j} \times |C|$$

The budget allocation of 6GAN could be represented as $(|C_1| : ... : |C_k|)$.

Evaluation

Pattern Discrimination

6GAN's discriminator can be optimized to achieve pattern discrimination.

- The overall accuracy of the discriminator reaches 0.966 scores for the 6 pattern types.

- 6GAN discriminator possess sufficient capacity to recognize addressing patterns in the IPv6 space.

Category	#Labels	# Preds	#Hits	#Errors	Accuracy
Embedded-IPv4	4.38k	4.54k	4.17k	0.37k	0.954
Embedded-port	0.57k	0.52k	0.50k	0.02k	0.898
IEEE-derived	3.19k	3.37k	3.18k	0.19k	0.998
Low-byte	12.82k	12.04k	11.93k	0.11k	0.931
Pattern-bytes	0.73k	1.49k	0.51k	0.98k	0.701
Randomized	28.31k	28.04k	28.02k	0.02k	0.990
Total	50.00k	50.00k	48.31k	1.69k	0.966

Evaluation

Performance of Alias Detection

Seed set

- 50k active addresses - 50k non-aliased addresses
- 50k source addresses - 7.9k aliased addresses and 42.1k non-aliased addresses

Seed set	Alias Detection	#Aliased Targets	Percentage
Active addresses	W/o	0.01k	0.02%
Active addresses	W/	0.00k	0.00%
Source addresses	W/o	6.91k	13.82%
Source addresses	W/	0.01k	0.02%

Ablation study results

- Training with non-aliased addresses - Recombining the aliased prefix during the sampling.
- Training with dataset containing aliased addresses - Greatly reducing the generation of aliased addresses.

- 6GAN's generator could intelligently avoid exploiting alias regions due to the reward guidance from the alias detector.
- High-quality candidate sets without wasting budgets.

Evaluation

Quality of Generated Addresses

Baselines

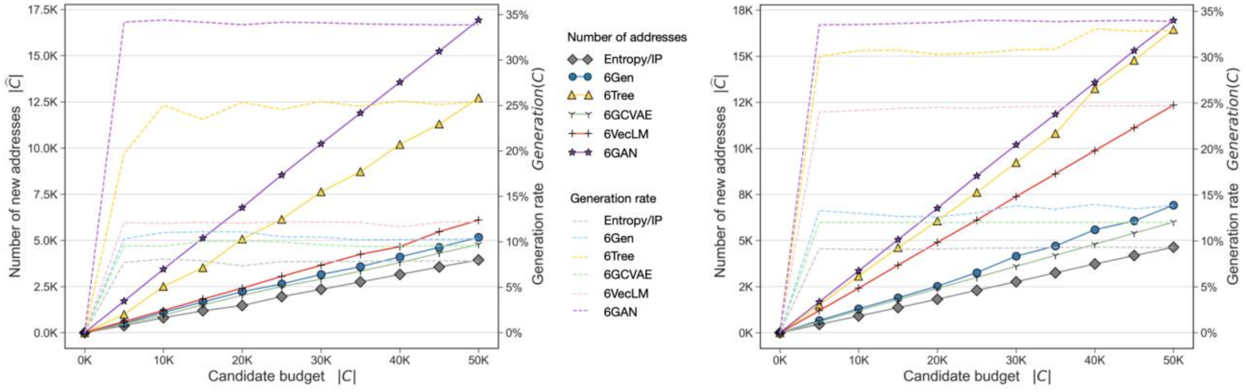
Approach	Target Generation	Alias Detection	Goal
Entropy/IP [13]	Analyzing addressing structures through information entropy	-	Visual address distribution
6Gen [14]	Searching the densest address clusters to provide active regions	Sampling scanning	Remarkable performance
6Tree [15]	Dynamic adjusting search directions with a space tree	Dynamic scanning	Faster time complexity
6GCVAE [16]	Reconstructing addresses through variational autoencoder	-	Deep learning attempts
6VecLM [17]	Predicting address sequences through language modeling	-	IPv6 semantics exploration
6GAN	**Multi-pattern target generation through adversarial training**	**Reinforcement learning**	**Higher-quality candidates**

- **Traditional Design Algorithms** - Entropy/IP, 6Gen, and 6Tree.
- **Deep Learning Approaches** - 6GCVAE, 6VecLM, and 6GAN.

Evaluation

Quality of Generated Addresses

Approach	Novelty(C)	Diversity(C)	Hit(C)	Generation(C)
Entropy/IP	12.37	6.80	12.03%	7.88%
6Gen	11.09	2.05	14.81%	10.33%
6Tree	11.16	2.06	24.40%	24.39%
6GCVAE	12.00	**7.66**	13.61%	9.50%
6VecLM	12.35	6.03	33.16%	12.20%
6GAN	**12.75**	4.73	**36.05%**	**33.21%**



(a) IPv6 Hitlist (b) CERN IPv6 2018

- 6GAN could generate creative addresses with high novelty quality.
- 6GAN obtains a not high diversity quality score.
- 6GAN outperforms all the baseline on the generation rate in our experiments.
- 6GAN could discover 1.03-1.33 times more active addresses than 6Tree.

Conclusion

- We propose **a novel architecture 6GAN** to generate diversified non-aliased active addresses of different addressing pattern types through using multiple generators guided by rewards from a discriminator and an alias detector.

- We employ **a multi-class objective of 6GAN's discriminator**, which can identify IPv6 addressing pattern categories.

- We implement **an alias detection approach embedded in the algorithm** by optimizing the generator, which saves algorithmic budget to generate high-quality candidates.

- We push the **quality of candidate sets** to a higher level. Experiments show that 6GAN outperforms state-of-the-art target generation algorithms on multiple metrics.

THANK YOU FOR LISTENING

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