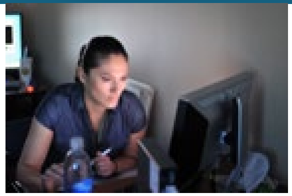
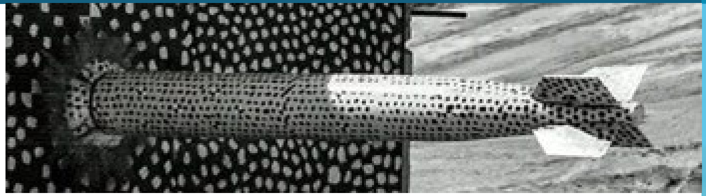
Moving Target Defense for Space Systems





SNL: Chris Jenkins, Eric Vugrin, Indu Manickum, Sarah Krakowiak, Richard "Grant" Brown, Jacob Hazelbaker, Nicholas Troutman, Josh Maxwell

Purdue: Prof. Bharat Bhargava, Marina Haliem, Ganapathy Mani

DEFCON 31 Aerospace Village

August 11, 2023

Sandia National Laboratories

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SAND2023-05208C

Agenda

Intro
- BLUF
- Why is this work being done?

Background
- Moving target defense
- MIL-STD-1553

MTD Algorithm
- State Generation
- Usage
- Randomness Characterization
- Unpredictability Quantification

Experimentation
- Setup
- Results

Machine Learning Attacks (done by Purdue)
- Methodology
- Results

Q&A

Background

Name: Chris Jenkins

Title: R&D S&E Cybersecurity

Degrees:

- B.S. Computer Engineering
- M.S. Computer Engineering
- PhD, Electrical Engineering (Computer Architecture, Minor: Computer Science)

How I got to SNL: Peoria → UIUC → UW Madison → Taiwan → San Diego → UW Madison → ABQ

First role at Sandia: EC-LDRD

- 1st patent
- 1st conference
- 1st publication

Now: Focus on HPC, OT, cybersecurity consultant for SMB through the SMPP & NMSBA

Latin Dance

- Salsa
- Bachata
- Merengue
- Cumbia

RV Trips

- Started in 2020
- Every year since then

Volunteer for STEM programs

- HMTech
- Dreamcatchers
- UNM

Sandia’s Impact

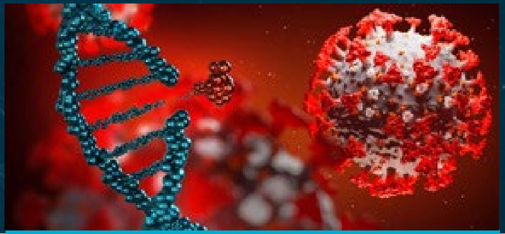
Sandia is often called upon to respond to high-profile events

Mars Perseverance rover

NASA’s Perseverance rover landed safely on Mars after a seven-month journey through space. The event could only take place following a safe launch that had been vetted by Sandia scientists.
(Courtesy of NASA/JPL-Caltech)

Cleanroom invented 1963

As the birthplace of the modern cleanroom, Sandia helped revolutionize manufacturing in electronics and pharmaceuticals and advance space exploration.
$50 billion worth of cleanrooms built worldwide.



COVID-19 Pandemic

Sandia has more than 50 COVID-related science and engineering projects that are designed to help the nation during the pandemic.

(Image by Loren Stacks)

Sustainable Energy

Sandia seeks to support the creation of a secure energy future for the US by using its capabilities to enable an uninterrupted and enduring supply of energy from domestic sources, and to assure the reliability and resiliency of the associated energy infrastructure.

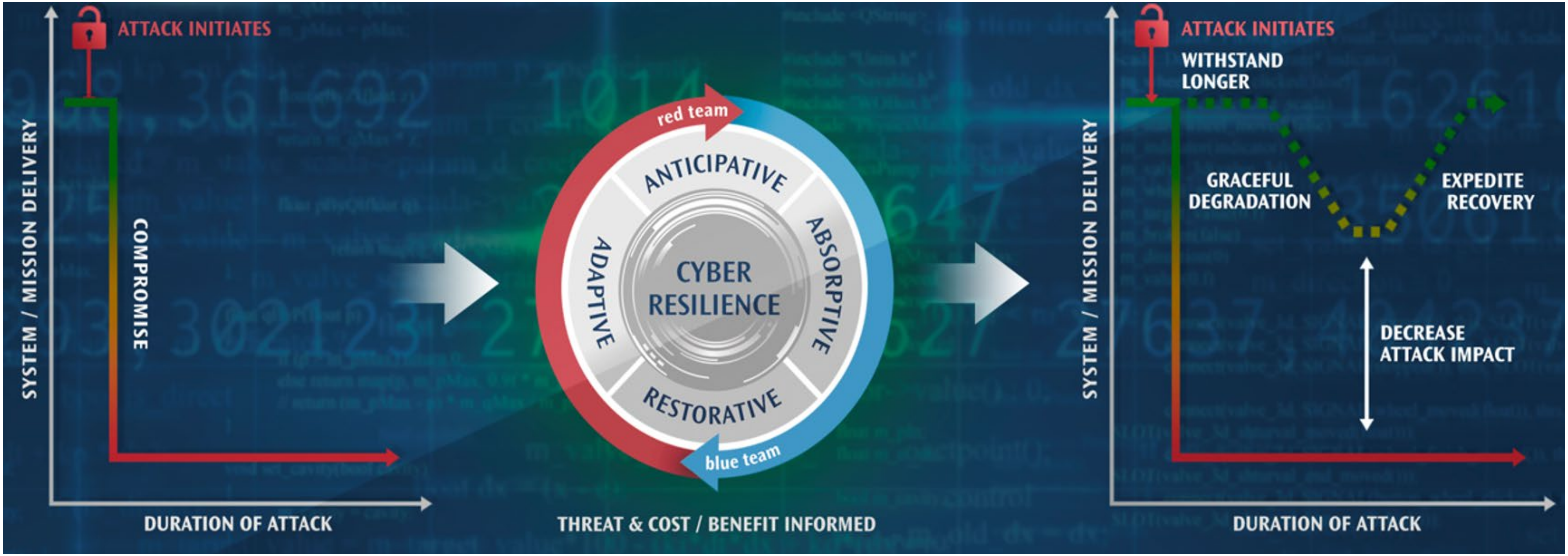
Learn the 70 ways Sandia has impacted our nation

U.S. National Laboratories

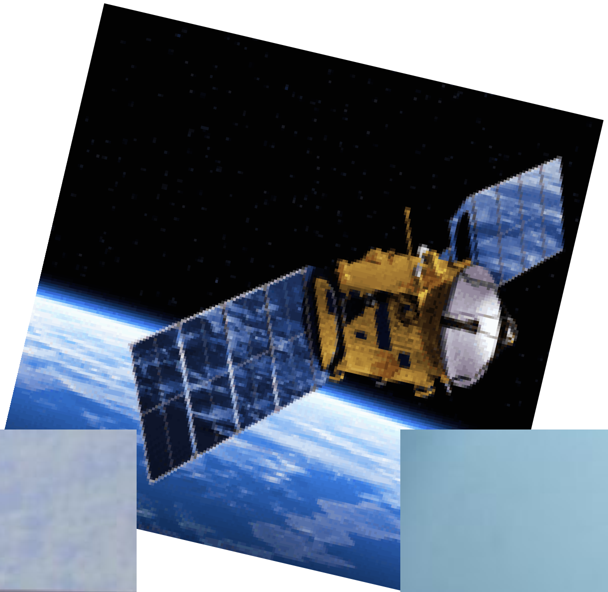
Sandia Has Two Main Locations

Intro

Cyber Security vs. Cyber Resilience



Protect Mission Systems



Concern: High consequence systems are becoming an attractive target for threat actors

BLUF

Accomplishments

- Patent awarded for MTD algorithm
- Obtained GUN copyright for MTD algorithm software (dll)
- NDA with commercial company
- Submitted to R&D100

Key Results

- Reduced adversarial knowledge by 97% during exfiltration cyber resilience experiment
- Quantified randomness and unpredictability of MTD algorithm
- Demonstrate resilience against machine learning attacks
- Generalized approach can be applied to various applications (not just address applications)

Publications

- 2021 IEEE Space Computing Conference (SCC)
- Sandia's FY21 Laboratory Directed Research & Development Annual Report (Page 39, https://user-cd6tqbe.cld.bz/Sandia-Labs-FY21-LDRD-Annual-Report)
- 2023 IEEE Transactions on Dependable and Secure Computing (TDSC)

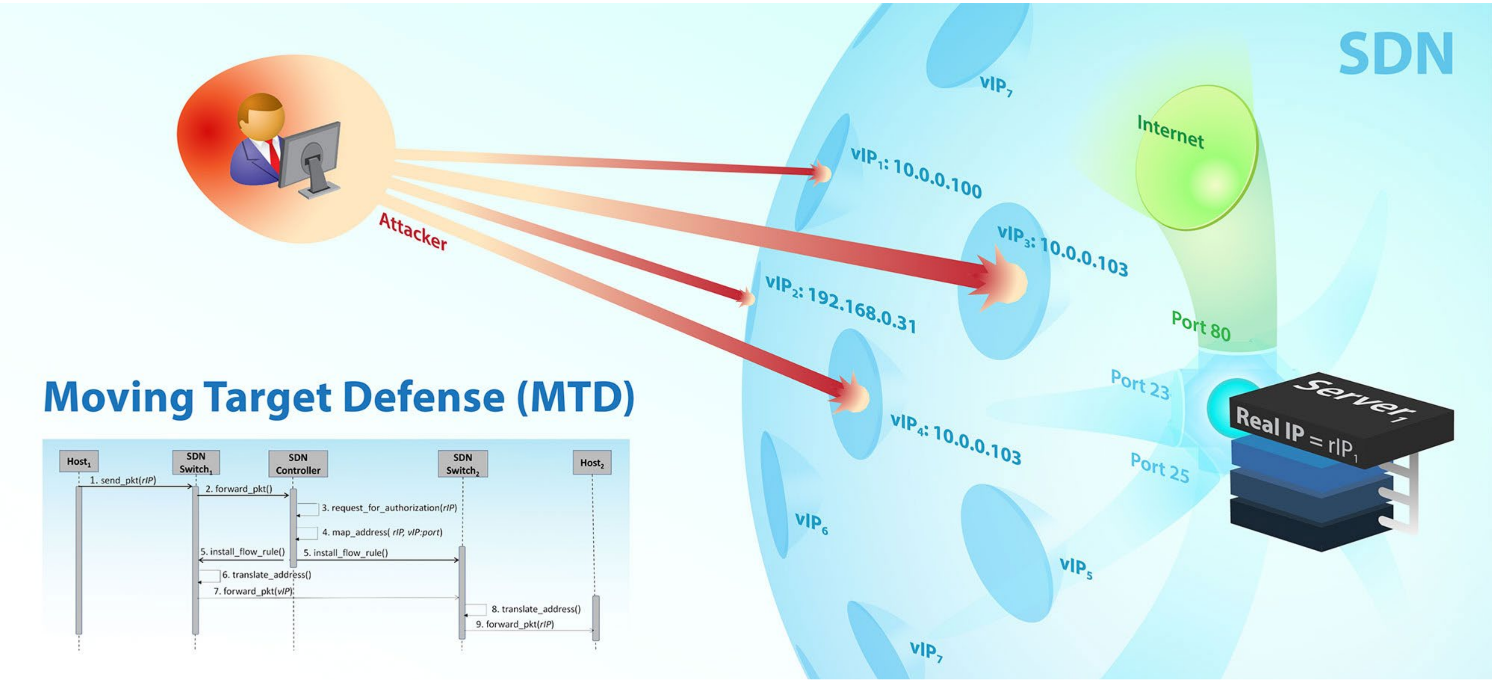
Presentations

- 2019 & 2022 Purdue CERIAS Seminar
- 2021 SNL Malware Technical Exchange Meeting (MTEM)
- 2022 Ground Systems Architecture Workshop (GSAW)

Background

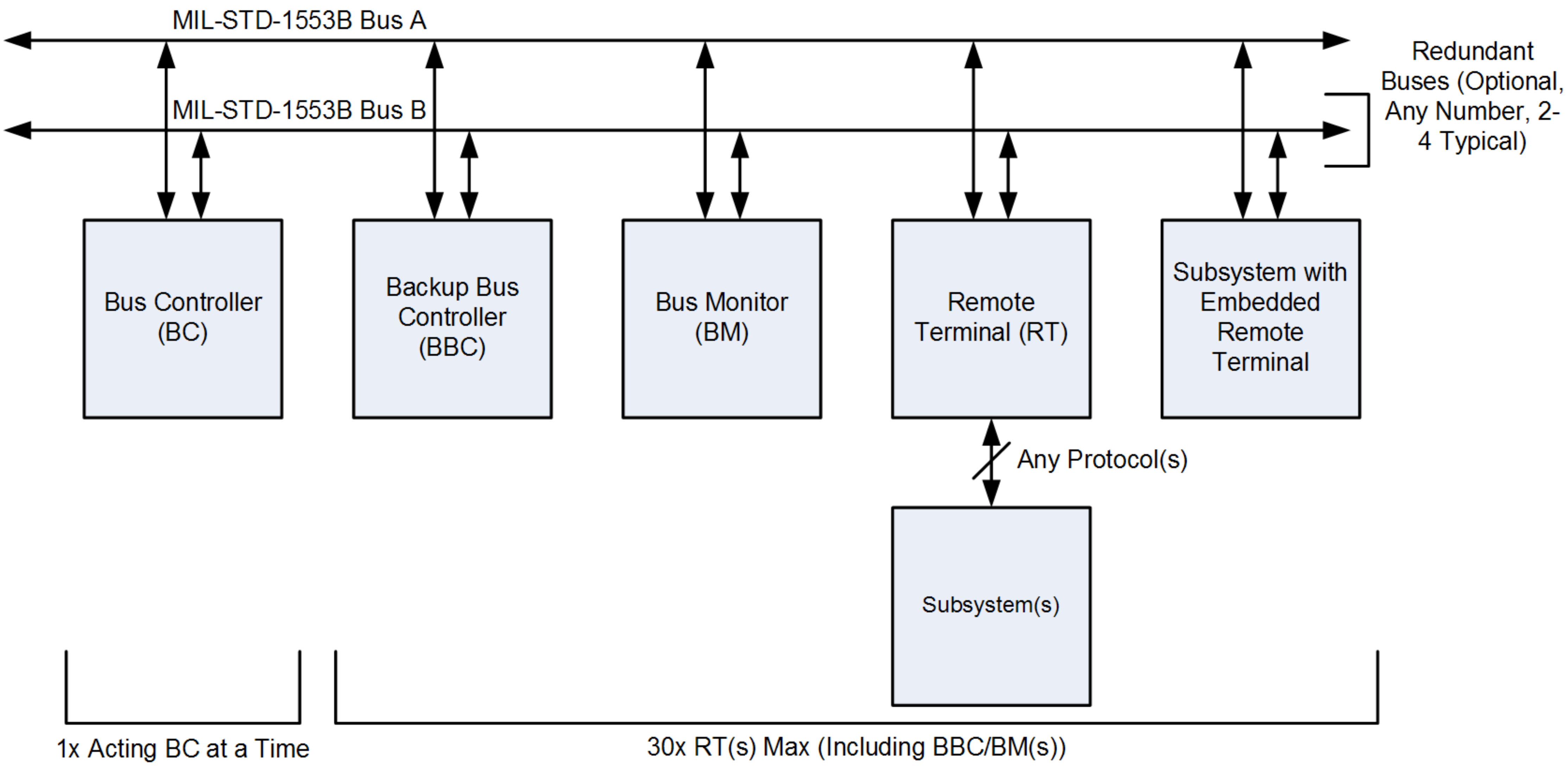
Moving Target Defense

- Dynamic reconfiguration of environment
- Randomly change node address after n messages
- Mitigates risk of an attacker guessing the correct addresses and injecting data



Hypothesis: MTD increases cyber resilience

MIL-STD-1553 Bus Architecture



Typical BC-RT Message


```
MESSAGE #2 ---------------------------------------
(89)17:22:30.074.576.560   IM Gap: 15154.6us
BUS A - CMD:1820 (3-R-1-32) BCRT
9EF3 1D47 FB99 A306 5A18 CAC8 BFEE 607D
FB0C ED27 27C5 04A9 22CE 6B31 A22A C0AF
9C44 15FA 086B D872 0E5F 187E 08BC CFB1
92EB 038A 7152 1D6D 388F 6EF6 4325 C051
Rsp Time 7.7us STS:1800
Message Time = 685.7us
```

Research Goals

Hypothesis: integration of MTD with a real -time protocol can increase cyber resilience of platforms using the protocol

Key Research Questions:

1. Can MTD be implemented in a manner that maintains operational constraints (e.g., accuracy, latency)?
2. Can we provide quantitative evidence that MTD does indeed improve cyber resilience?

Uniqueness: Real-time, SWaP constrained systems

Uniqueness: Doesn't require anomaly detection

MTD Algorithm

Design Challenges

Keep underlying protocol – determinism, predictability, reliability, and real-time operation

Dynamic address generation – each node must index or use a disjoint set of addresses as compared to other nodes on the network. Also, have the ability to increase or decrease speed of address hopping

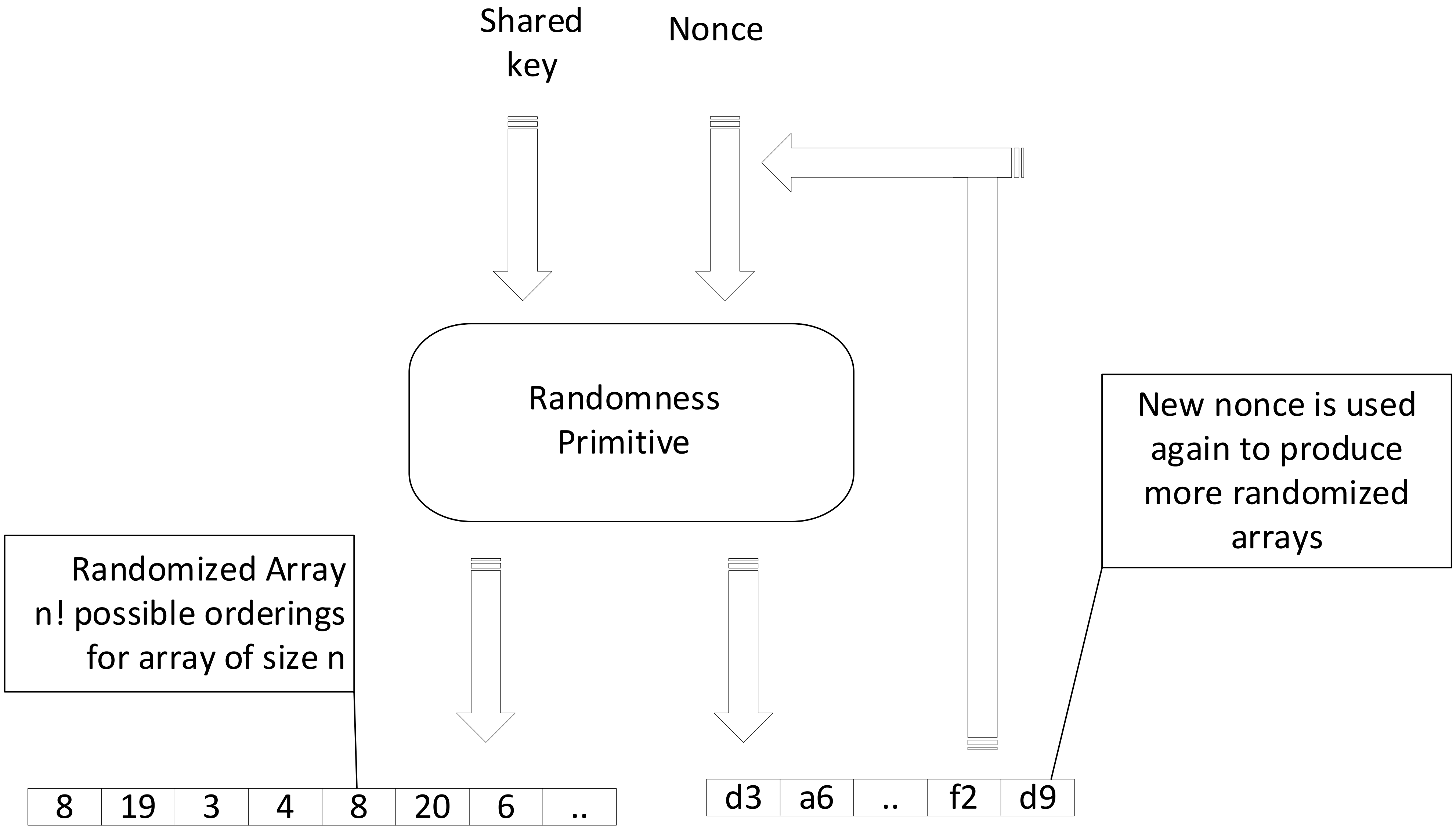
Synchronization – provide fast recovery if a device loses sync

Entropy – provide enough randomness

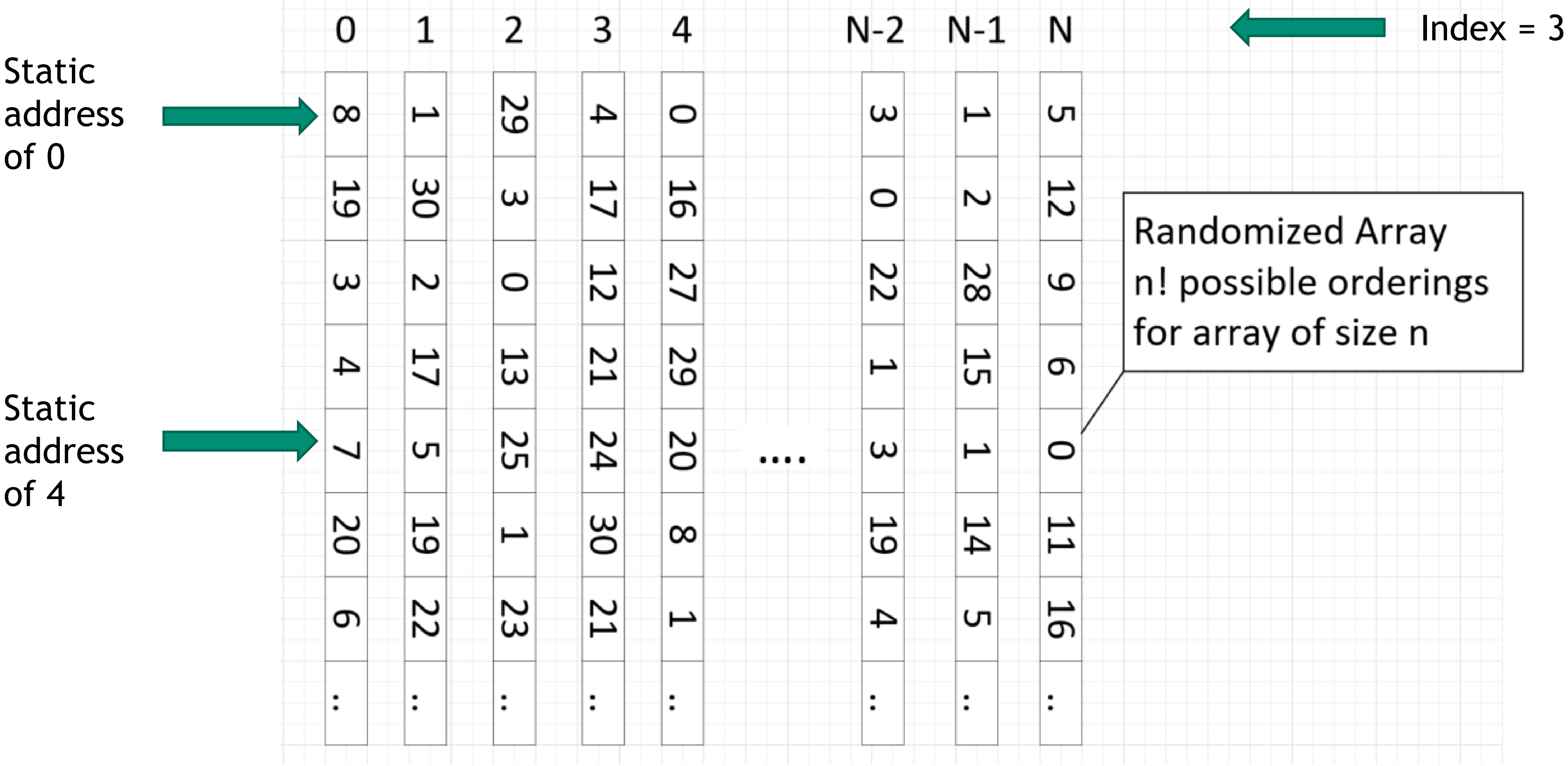
Periodicity – provide sufficiently long hopping patterns

Authenticity – determine if MTD commands are authentic using analog signatures, MACs, MICs, etc.

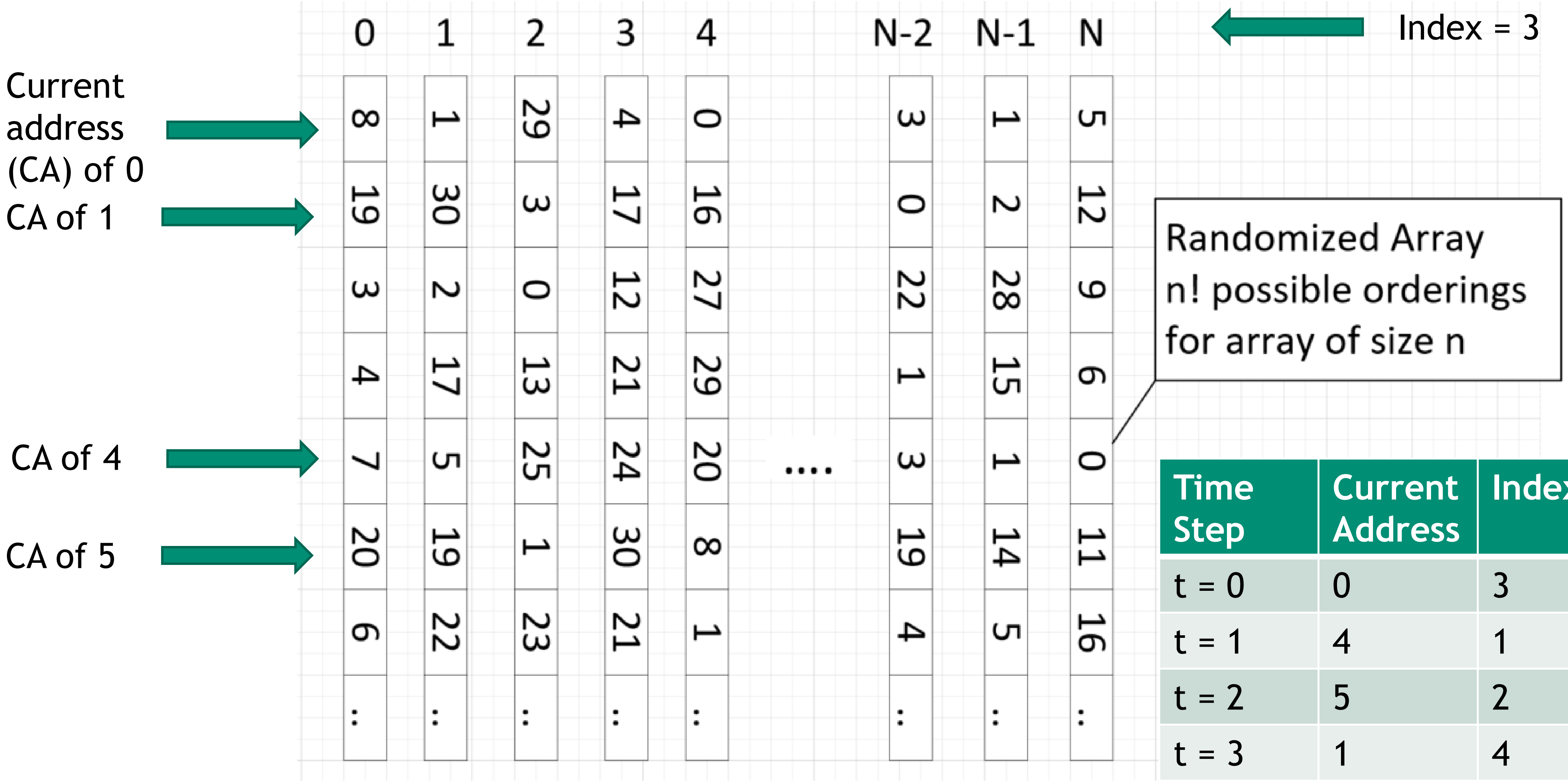
MTD Algorithm



State Matrix (Arrays) – Static Offset

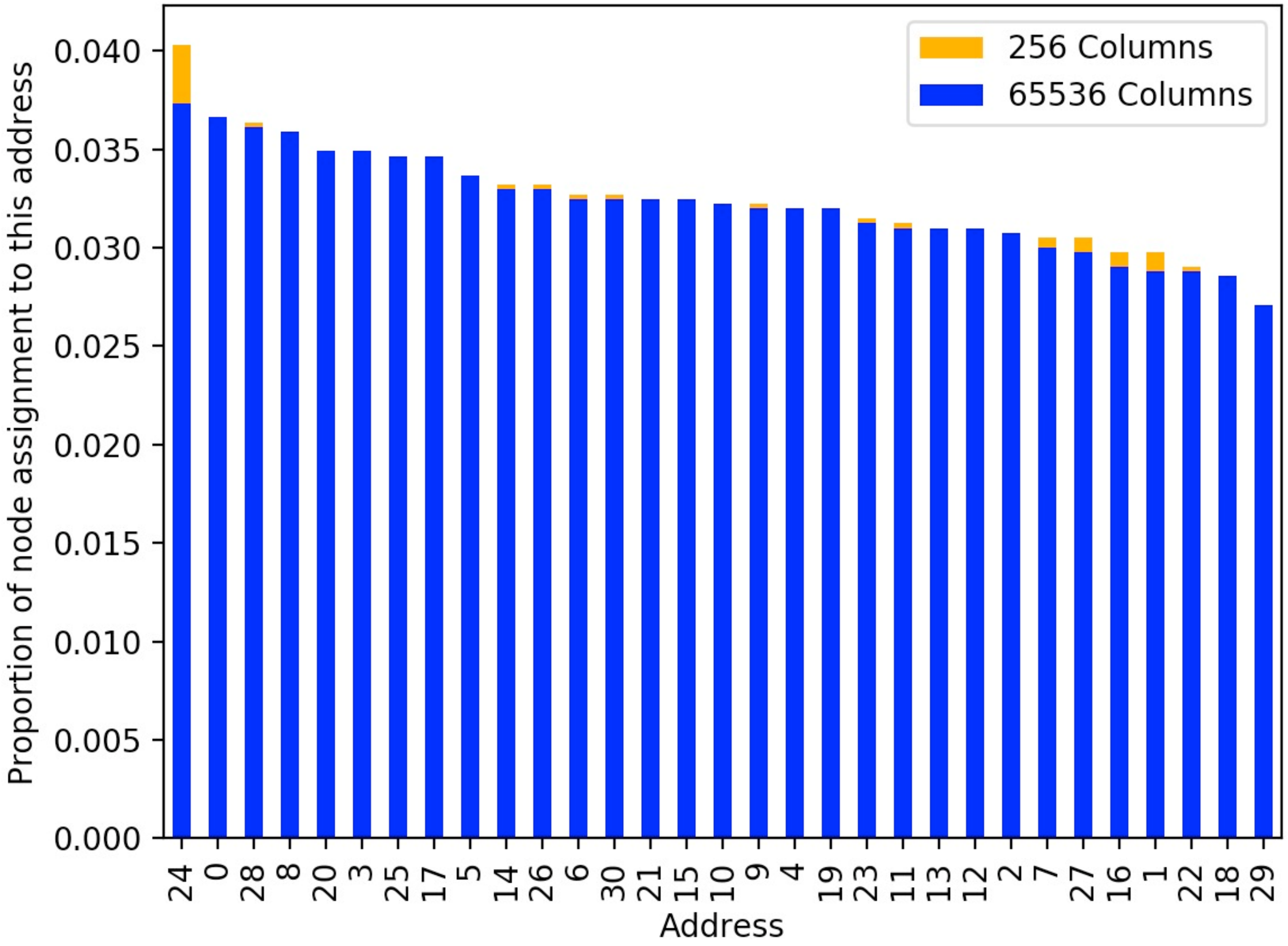


State Matrix (Arrays) – Current Offset



Time Step	Current Address	Index	Next Address
t = 0	0	3	**4**
t = 1	4	1	**5**
t = 2	5	2	**1**
t = 3	1	4	**16**

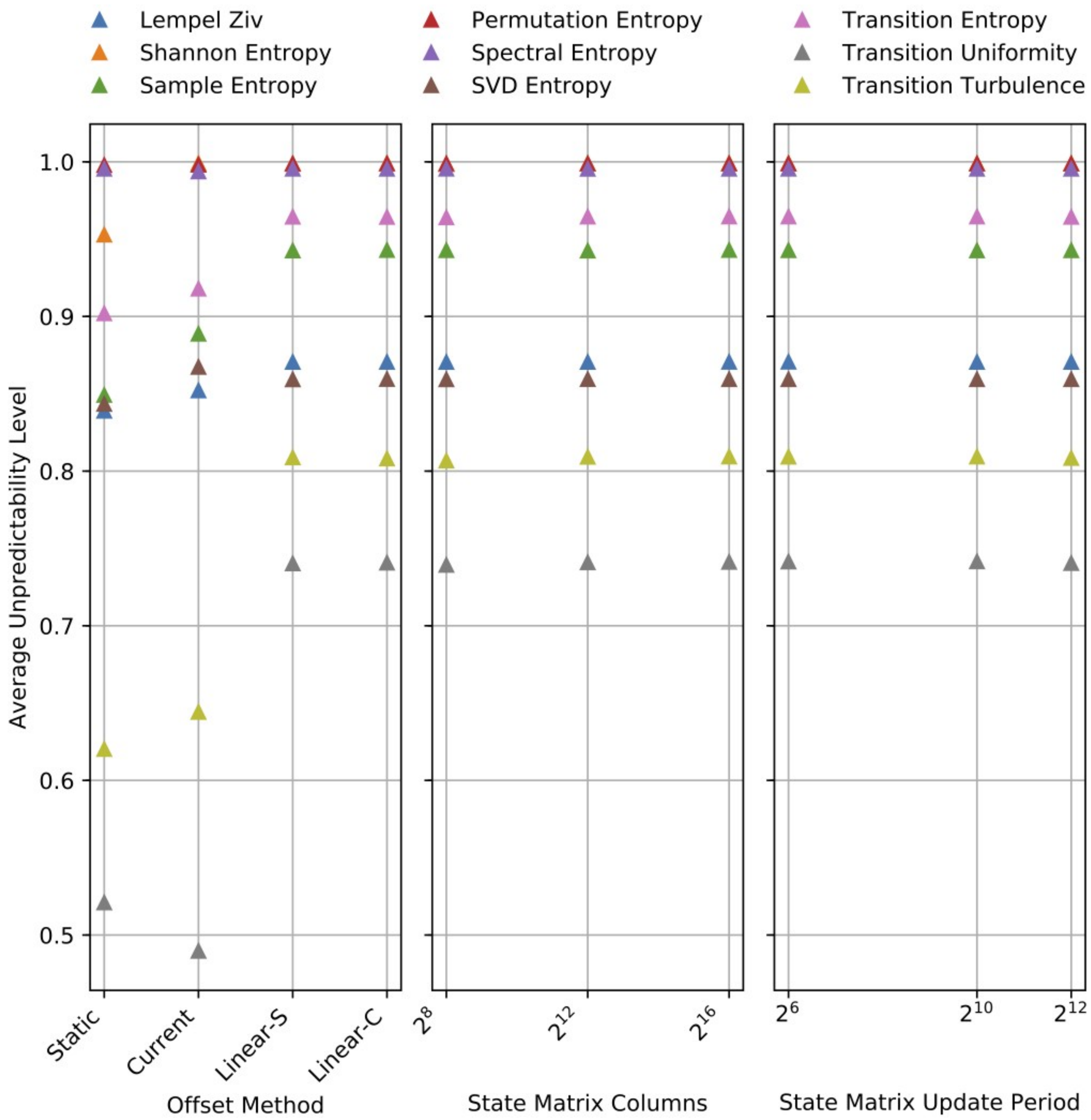
Entropy Results



Preliminary findings

- Frequency of addresses is not perfectly uniform, leaving some area for improvement
- Entropy for 256 columns is 0.9984
- Entropy for 65536 columns is 0.9989

Unpredictability Results



Analysis Process

1. Create 10 state matrices with 10 PRNG seeds
2. For each matrix, 31 address sequences (one for each node) for each of the 12 unique combinations of offset and matrix size (3,720 sequences)
3. Each sequence has a length of 4,096
4. Calculate set of 9 unpredictability metrics and average over 31 address sequences per state matrix and unique combination

- For update period, concatenated multiple matrix sequences to simulate state matrix updates

Preliminary findings Period

- Offset method has most effect on unpredictability metrics
- Number of state matrix columns and update period do not appear to significantly affect unpredictability

Experimentation

MIL-STD-1553 Research Plan

Phase 1: Calculate Fibonacci sequence w/ and w/o MTD

- Run experiment to obtain the 24th Fibonacci number
- Run experiment with MTD and update the address after every X frames (2 messages per frame)
- Due to low amount of messages, compute multiple times–we call this a generation

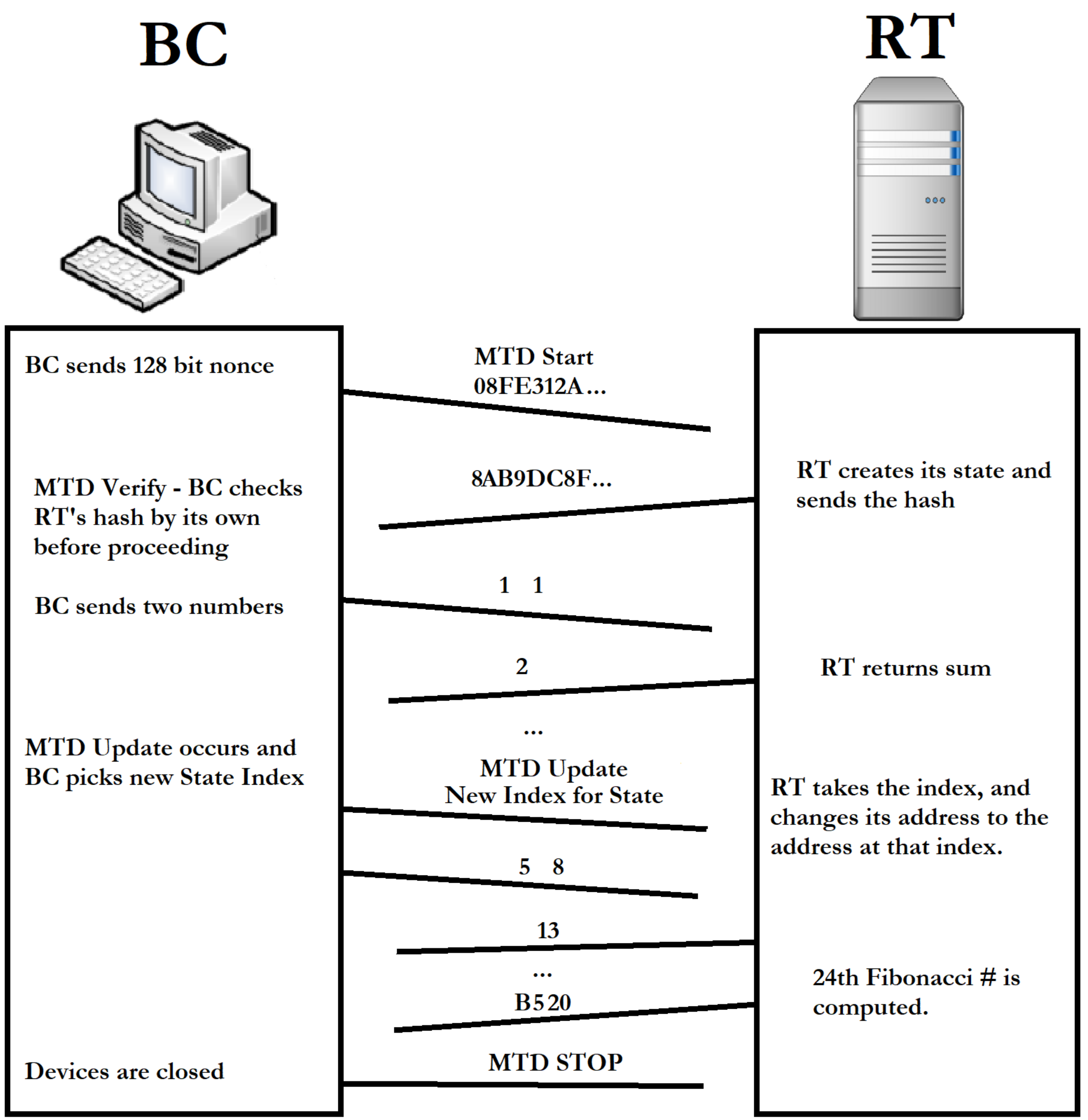
Phase 2: Exfiltration

- Exfiltration data from target node on MIL-STD-1553 network
- Goal: Quantify reduction in adversarial knowledge

ENET2-1553


Alta dt
data technologies
eNet-1553
Model
Part No
SN
Made in USA
J1
J2
PWR BIT
ETH LNK
ETH ACT
1553 ACT

Phase I


BC
RT
BC sends 128 bit nonce
MTD Start
08FE312A…
RT creates its state and sends the hash
8AB9DC8F…
MTD Verify - BC checks RT's hash by its own before proceeding
BC sends two numbers
1 1
2
RT returns sum
…
MTD Update occurs and BC picks new State Index
MTD Update
New Index for State
RT takes the index, and changes its address to the address at that index.
5 8
13
…
B520
24th Fibonacci # is computed.
Devices are closed
MTD STOP

MTD Commands

MTD Start

```
MESSAGE #1 ------------------------------------------
Time: [2019](218)14:19:50.152.086.960   IM Gap: 49202281us
BUS A - CMD:F828 (31-R-1-8) BRDCST BCRT
0000 0026 0000 1E27 0000 52F6 0000 0985
Message Time = 180us
```

BC's 128-bit Nonce

MTD Verify

```
MESSAGE #2 ------------------------------------------
Time: [2019](218)14:19:50.307.529.360   IM Gap: 155264.5us
BUS A - CMD:0CC0 (1-T-6-32) RTBC
Rsp Time 6.5us STS:0800
D541 934B 0B33 FF99 FFA8 3C5B FF94 FF9F
0106 6A45 FF81 E84A FF95 FF8A 385E 4F40
214A 055E FFAA 3364 FFCA FFD0 FFF0 2D78
FFCB E257 FFCC D378 DA40 FF91 930E FF8C
Message Time = 684.5us
```

Hash of State

MTD Update

```
MESSAGE #15 ------------------------------------------
Time: [2019](218)14:19:50.385.049.880   IM Gap: 13739.9us
BUS A - CMD:F841 (31-R-2-1) BRDCST BCRT
0017
Message Time = 40us
```

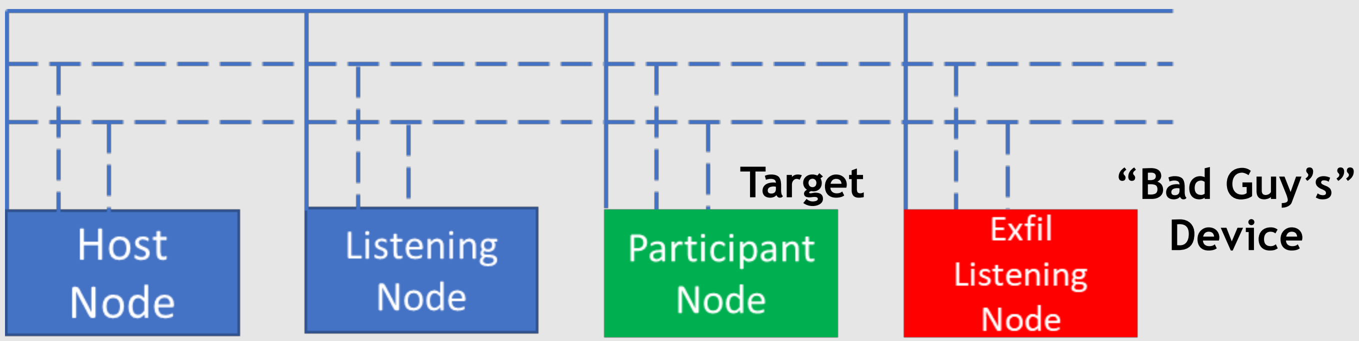
New Index for RT's State

Finished

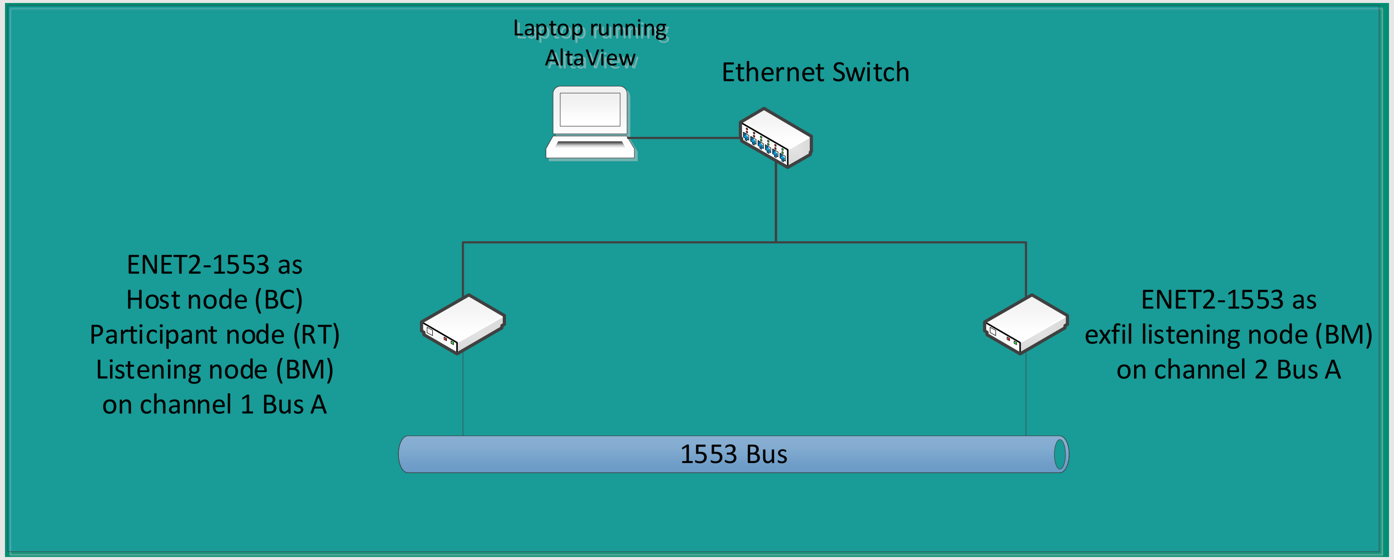
```
MESSAGE #117 ----------------------------------------
Time: [2019](218)14:19:51.019.122.240   IM Gap: 9041.6us
BUS A - CMD:E882 (29-R-4-2) BCRT
452F 6FF1
Rsp Time 6.5us STS:E800
Message Time = 84.5us

MESSAGE #118 ----------------------------------------
Time: [2019](218)14:19:51.020.207.240   IM Gap: 1002.6us
BUS A - CMD:ECA1 (29-T-5-1) RTBC
Rsp Time 6.5us STS:E800
B520
Message Time = 64.5us
```

24th Fibonacci #

Resilience Expt.: Exfiltration Attack Scenario



System of Interest



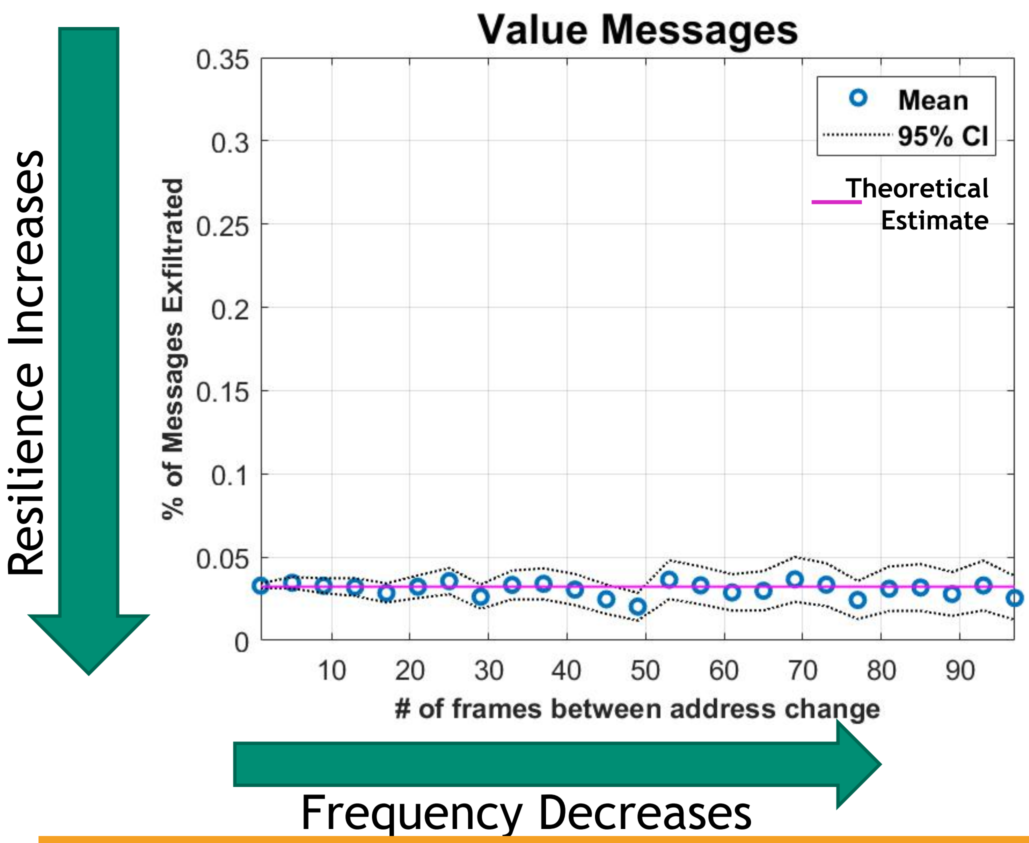
Experimental Set Up

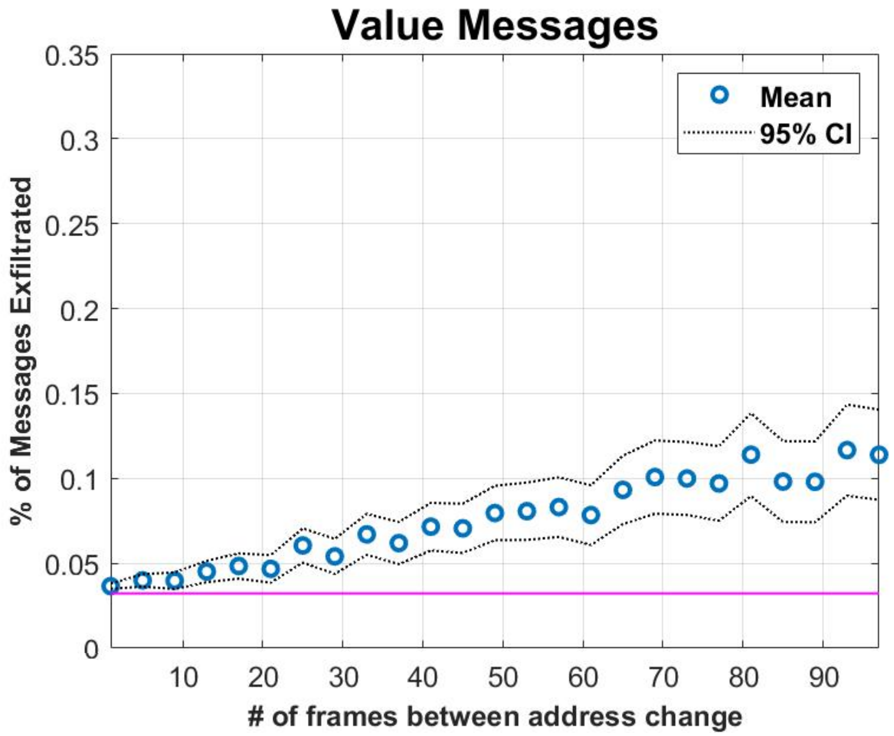
Set Up

- Attacker has corrupted an node to be an exfil listening node (red)
- Messages to/from target participant node (green) = messages of value to the attacker
- Exfil listening node monitors & exfils all messages to/from target
- With no MTD, exfil listening node will see and exfil 100% of messages to/from target

Question: does the implementation of MTD reduce the fraction of "messages of value" that are exfiltrated?

Exfil Expt.: Results





In this scenario

- MTD reduces % of value messages exfiltrated by ~97%
- Experimental results match theoretical estimates

When the adversary knows the starting address for the target

- Low frequencies give poorer results in the expts
- This observation is due to relatively short length of experiments (50 generations)
- When the length is increased, the expected # of messages exfiltrated decrease closer to 3%

Machine Learning

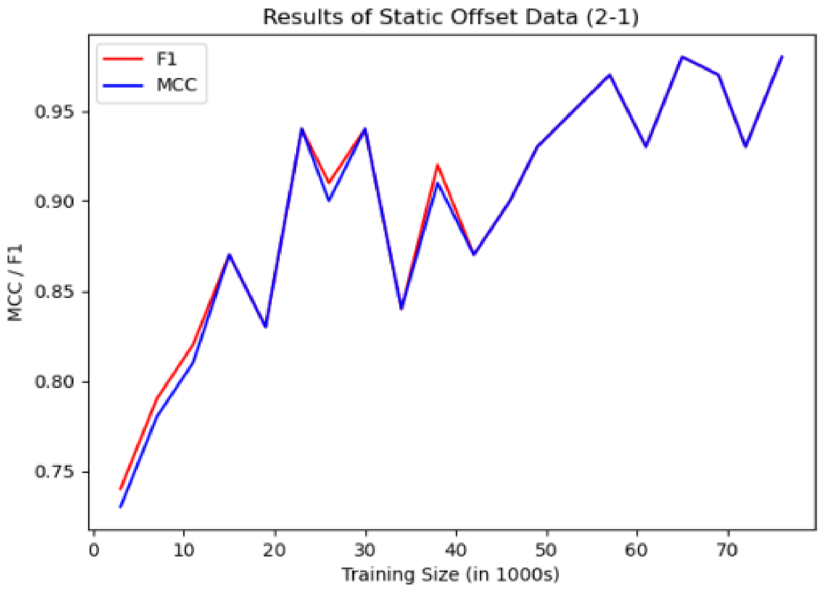
MTD Update Message

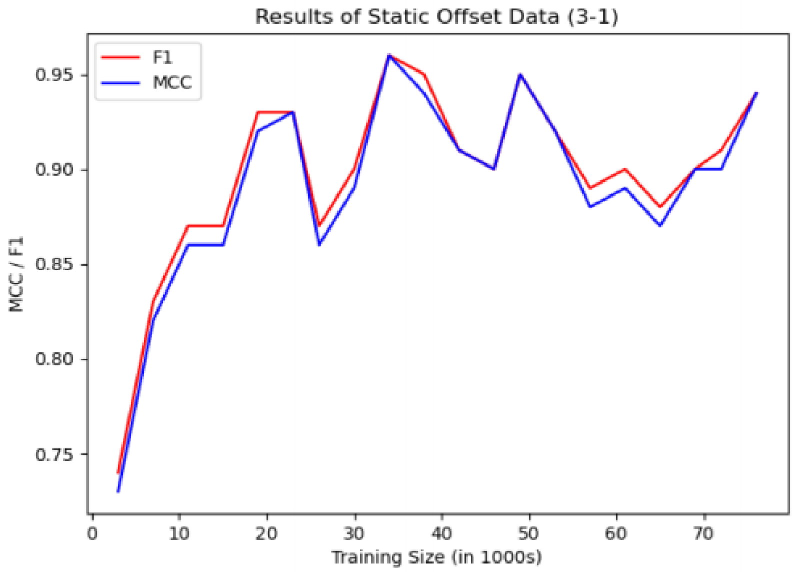
```
MESSAGE #13 -------------------------------------------
Time: [2019](218)14:19:50.370.162.640   IM Gap: 7407.6us
BUS A - CMD:0882 (1-R-4-2) BCRT
0002 0003
Rsp Time 6.5us STS:0800
Message Time = 84.5us

MESSAGE #14 -------------------------------------------
Time: [2019](218)14:19:50.371.247.640   IM Gap: 1002.6us
BUS A - CMD:0CA1 (1-T-5-1) RTBC
Rsp Time 6.5us STS:0800
0005
Message Time = 64.5us

MESSAGE #15 -------------------------------------------
Time: [2019](218)14:19:50.385.049.880   IM Gap: 13739.9us
BUS A - CMD:F841 (31-R-2-1) BRDCST BCRT
0017
Message Time = 40us

MESSAGE #16 -------------------------------------------
Time: [2019](218)14:19:50.397.934.480   IM Gap: 12846.7us
BUS A - CMD:D882 (27-R-4-2) BCRT
0003 0005
Rsp Time 6.5us STS:D800
Message Time = 84.5us

MESSAGE #17 -------------------------------------------
Time: [2019](218)14:19:50.399.019.440   IM Gap: 1002.6us
BUS A - CMD:DCA1 (27-T-5-1) RTBC
Rsp Time 6.5us STS:D800
0000
Message Time = 64.5us
```

ML Experimentation

- Given a log of all messages on the bus
  - ~~Can you figure out the state matrix?~~
  - Can you identify MTD messages?
  - **Can you determine the next address?**
  - ~~Are any other side channels present?~~
- Models Used
  - LSTM model for predicting the next address
  - Varied the number of previous addresses the model remembers
  - Training size varied
  - Test size always 20% of total data

ML Results (from Purdue University)





Future Work

Future Work

Seek to become a MTD NIST standard (do any exist?)

Employ SOTA ML techniques to defeat algorithm

Apply to existing MTD framework (ADDSec, SNL MTD technology)

- Apply to TCP port encryption
- Apply IPv4 address randomization
- One static key for all packets → 3 separate keys per packet

Apply to host-based randomization techniques (e.g., ASLR, KASLR)

Transparent (dynamic) file-system

Synchronizing keys

Apply to computer architecture techniques (e.g., MTE, PAC, SVM, SME)

Rolling codes for embedded devices (e.g., key fobs)

Thank you!

Backup

Fulfilling Our National Security Mission

Global Security

Nuclear Deterrence

National Security Programs

Energy & Homeland Security

Advanced Science & Technology

[illegible]

Some of the critical national security issues that we address lie in the cyber area.

Offset Methods

Index – 16-bit index

Static – use static address as offset

Current – use current address as offset

Offset Selection Mechanism		Index Interpretation	
		Unsigned integer	**Linear combination**
Address Used	**Initial address**	Static	Linear-static
	Current address	Current	Linear-current

16-bit index: 10-bit (sub-)index, 3-bit multiplier, 3-bit adder

Linear static (Linear-S) – c is the static address

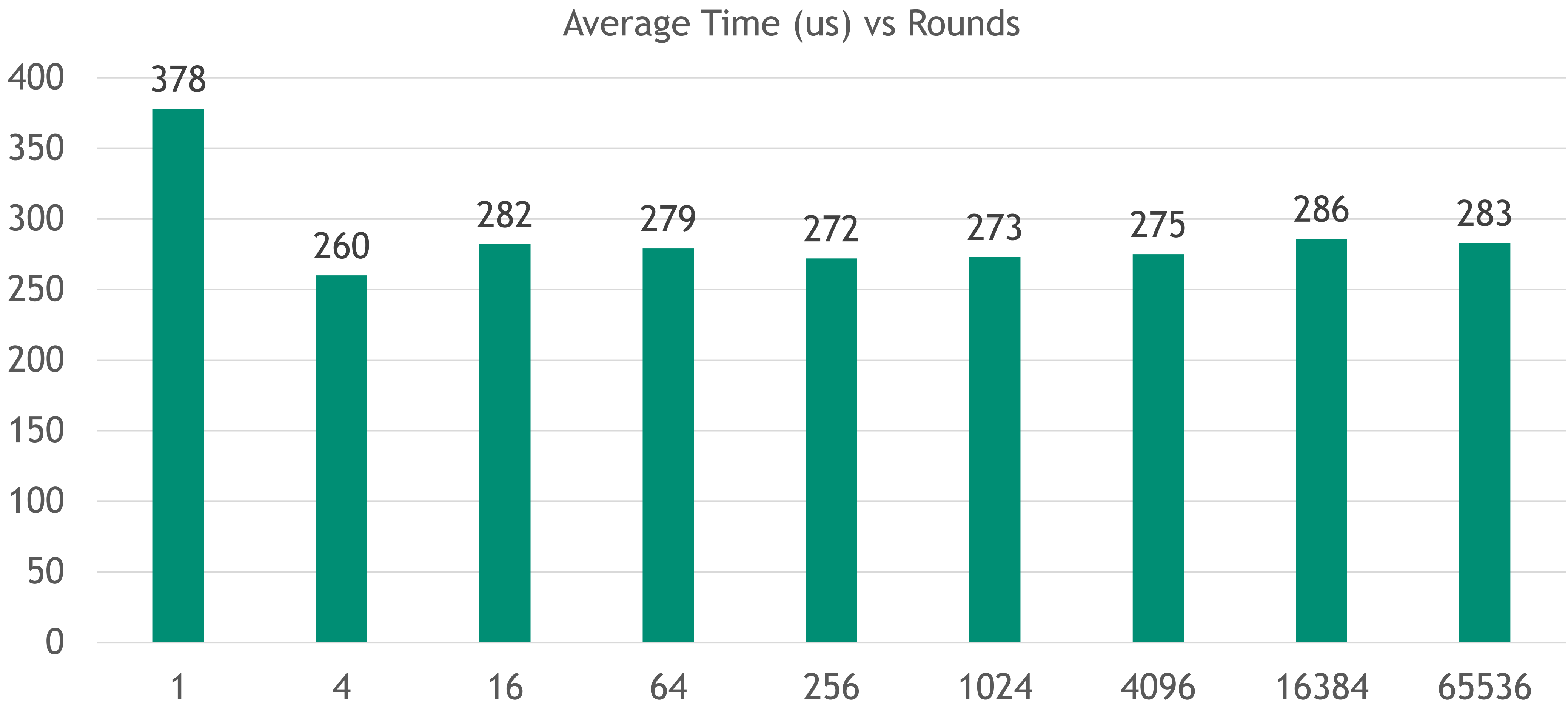
Linear current (Linear-C) – c is the current address

4a+b+c mod n = d, where a, b, c, d, and n are unsigned integers

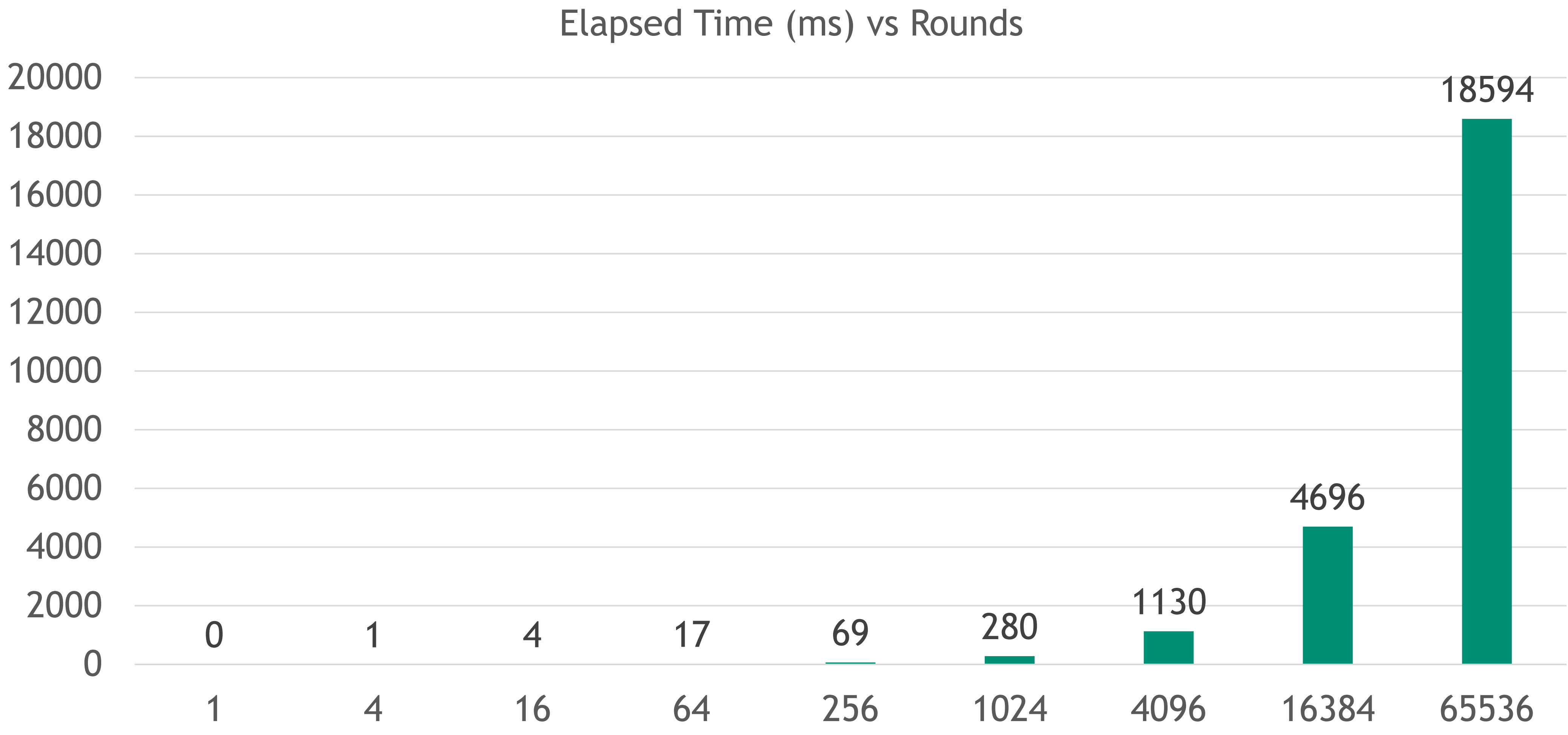
Space Requirements for State Matrix

Number of Arrays	Approximate Size (KB = 1024)
1	0.03125
4	0.125
16	0.5
64	2
256	8
1024	32
4096	128
16384	512
65536	2048

State Matrix Column Generation Performance



State Matrix Generation Performance



MTD Algorithm Summary

All addresses are not created equal (non-uniform distribution)

All addresses are used given enough time

Don’t need large matrix to have good entropy

Index into state (or states) (don’t generate state array on-the-fly)

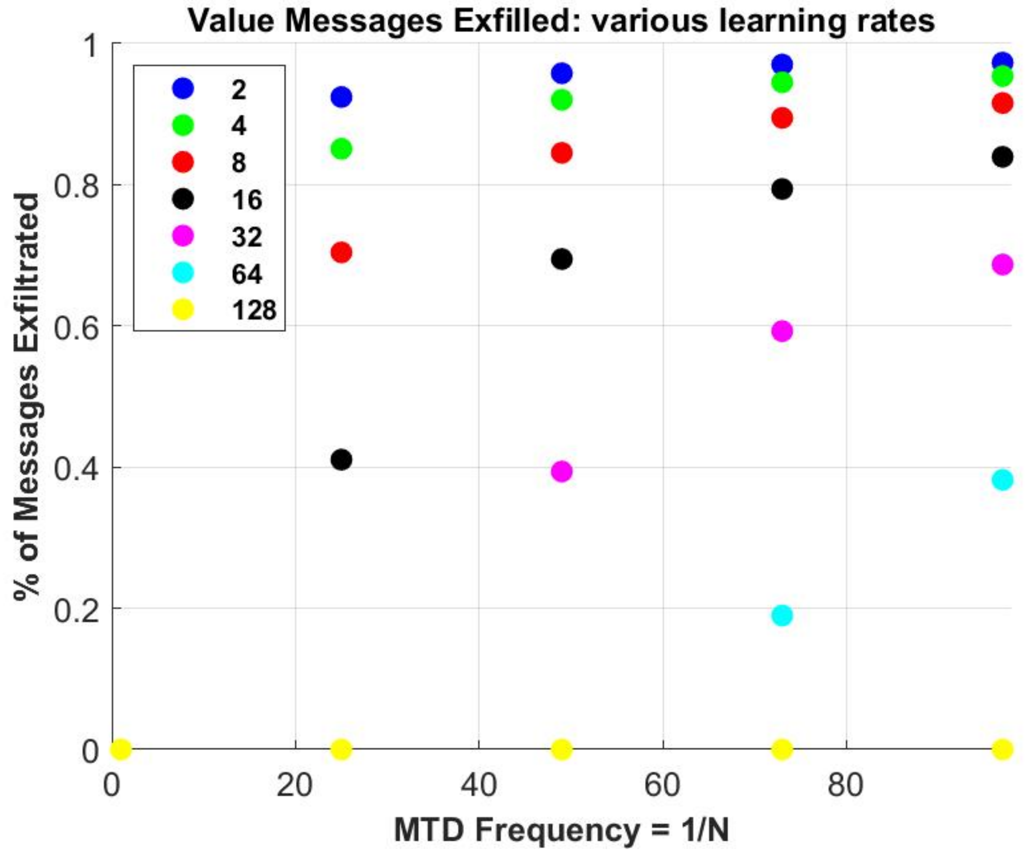
Try different primitive (AES, LFSR, RDRAND, etc.)

Non-address attributes or different size addresses may not have same profile

Required indexes to see all possible addresses (Random Index)

Cell Offset Method	# of columns	Total	Average	Minimum	Maximum	Std. Dev
Static	512	7686	247.96	87	606	136.82
Current	512	4083	129.13	65	278	38.14
L-Static	512	5842	188.45	85	384	70.32
L-Current	512	3988	128.64	71	239	40.36
Static	8192	5934	191.42	86	369	77.55
Current	8192	3855	124.35	71	204	36.18
L-Static	8192	4272	137.81	87	270	37.20
L-Current	8192	4259	137.39	67	244	45.07
Static	65536	5501	177.45	75	351	74.52
Current	65536	3827	123.45	71	196	33.34
L-Static	65536	3756	121.16	61	246	36.77
L-Current	65536	3587	115.71	77	198	28.72

Exfil Expt. Results: Learning Adversary



1000 Fibonacci Generations, 25 trials

Assume adversary learns new address after X frames

Example:

- Period = 25, learned = 8 frames, exfil = 70%
- Period = 25, learned = 16 frames, exfil = 40%
- Period = 25, learned = 32, exfil = 0%

Takeaways:

- Against a learning adversary, MTD frequency needs to be faster than adversary learning rate to significantly mitigate exfil attacks
- These data can start informing design requirements