ERW-Radar: An Adaptive Detection System against Evasive Ransomware by Contextual Behavior Detection and Fine-grained Content Analysis

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Background

■ Traditional ransomware

Encrypt a large number of files in short time, and demand ransom from victims to restore the encrypted files

Anomalous I/O behaviors

- ➢ High frequency of I/O requests
- ➢ Specific behavior patterns (e.g., read-encrypt-delete)
- ➢ High entropy values of files

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Evasive ransomware

Successfully encrypt the files and bypass ransomware detection systems

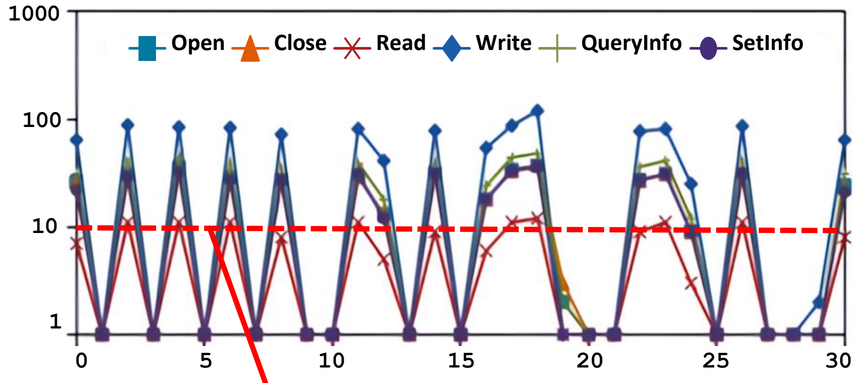
Encryption efficiency

Weakened or even hidden malicious features of I/O behaviors

Background

■ Evasive ransomware-a

- **Evasive strategy:** adjust I/O strategy to make operations less intensive or regular
- **E.g.,** split short-duration encryption tasks and run sub-tasks intermittently



I/O frequency

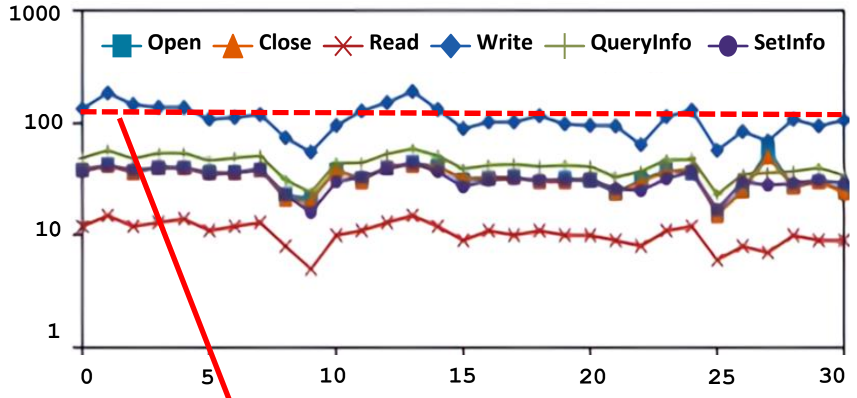
Existing approaches

Features:

- Number of read, write, delete … operations
- Sequence of operations

Limit:

- Rely heavily on predefined features or specific patterns (fixed detection threshold)

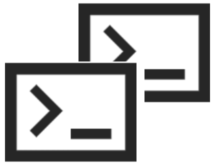


Detection threshold

Background

■ Evasive ransomware-b

- **Evasive strategy:** achieve encryption goal by imitating benign programs
- **E.g.**, extract behavior templates and use them to orchestrate attack



Template A					
Time	Proc	Operation	Path	Entropy	R/W Size
T_0+t_i	P_i…	QueryInfo	Dir_1…	/	/
T_0+t_j	P_j…	Read	F_1…	/	4096B
T_0+t_k	P_k…	DirControl	F_2…	/	/
T_0+t_l	P_l…	Create	F_3…	/	/
T_0+t_m	P_m…	Write	F_4…	6.12	1024B
T_0+t_n	P_n…	CleanUp	F_5…	/	/
…	…	…	…	…	…

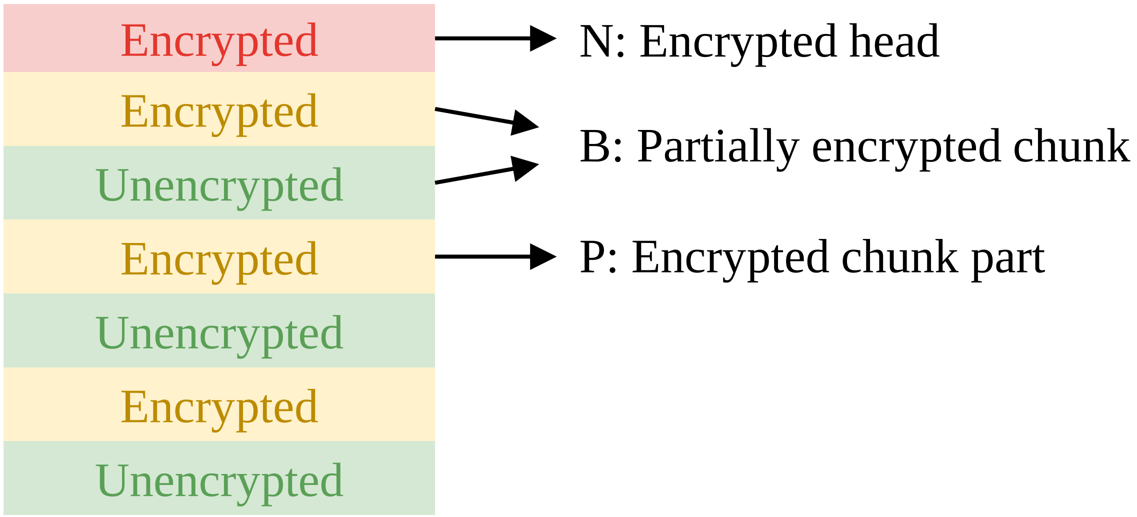
Limit of existing approaches:

- Assume that ransomware behaves very differently from benign programs due to frequently encrypting files and erasing original content

Background

■ Evasive ransomware-c

- **Evasive strategy:** use partial encryption or pad low-entropy data to reduce entropy values
- **E.g.**, The Blackcat ransomware, which adjusts N, B, and P to implement various encryption methods, including Full Pattern, Head Only Pattern, Dot Pattern, and Smart Pattern



Limits of existing approaches:

- Rely heavily on high entropy values of encrypted files

Threat model

Evasive ransomware

- Evade detection systems by adopting mainstream evasive techniques rather than simplifying encryption operations (directly deleting files)

Crypto ransomware

- Encrypt the majority of file content to ensure that files cannot be read or recovered by victims, rather than using non-encryption content hiding techniques (setting passwords for files)

Exclusion ransomware

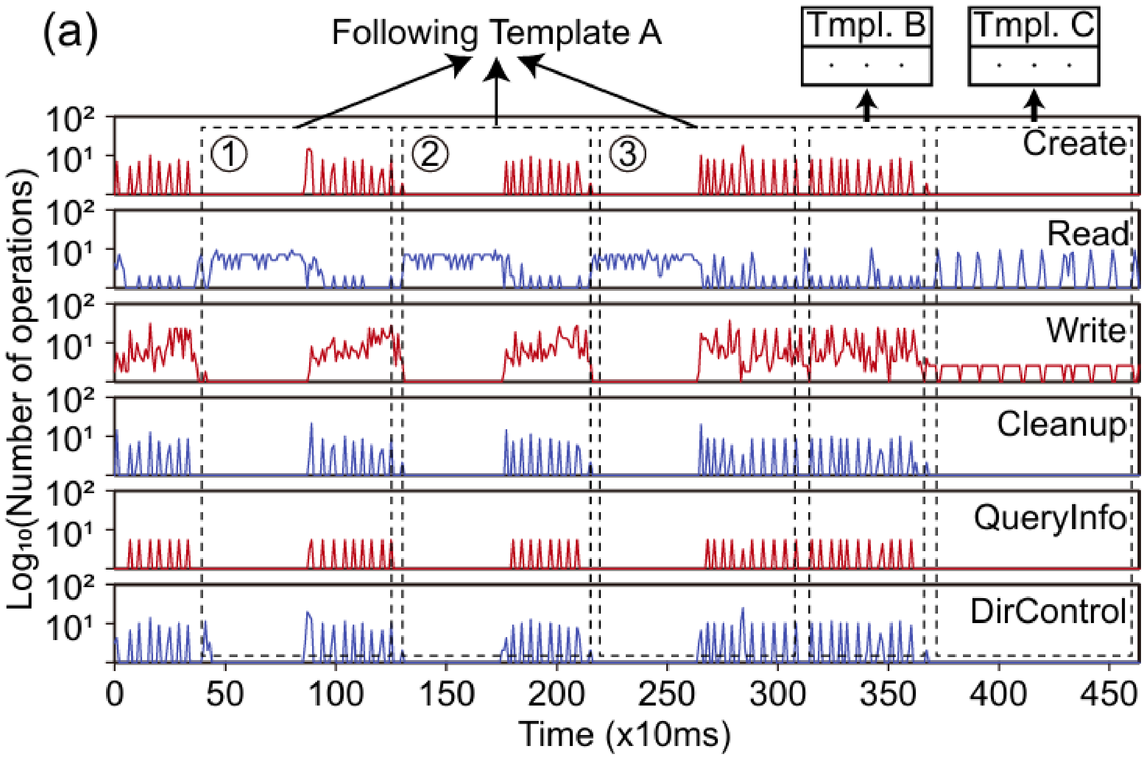
- Encrypt at extremely slow speeds (one byte/hour speed)

System shutdown

- The detection system is monitored and managed in secure environment (entrust the management of ERW-Radar to the ASP, which has the highest privilege of the system)

Can we design a system that can defend against these attacks?

Observation & Opportunity-1



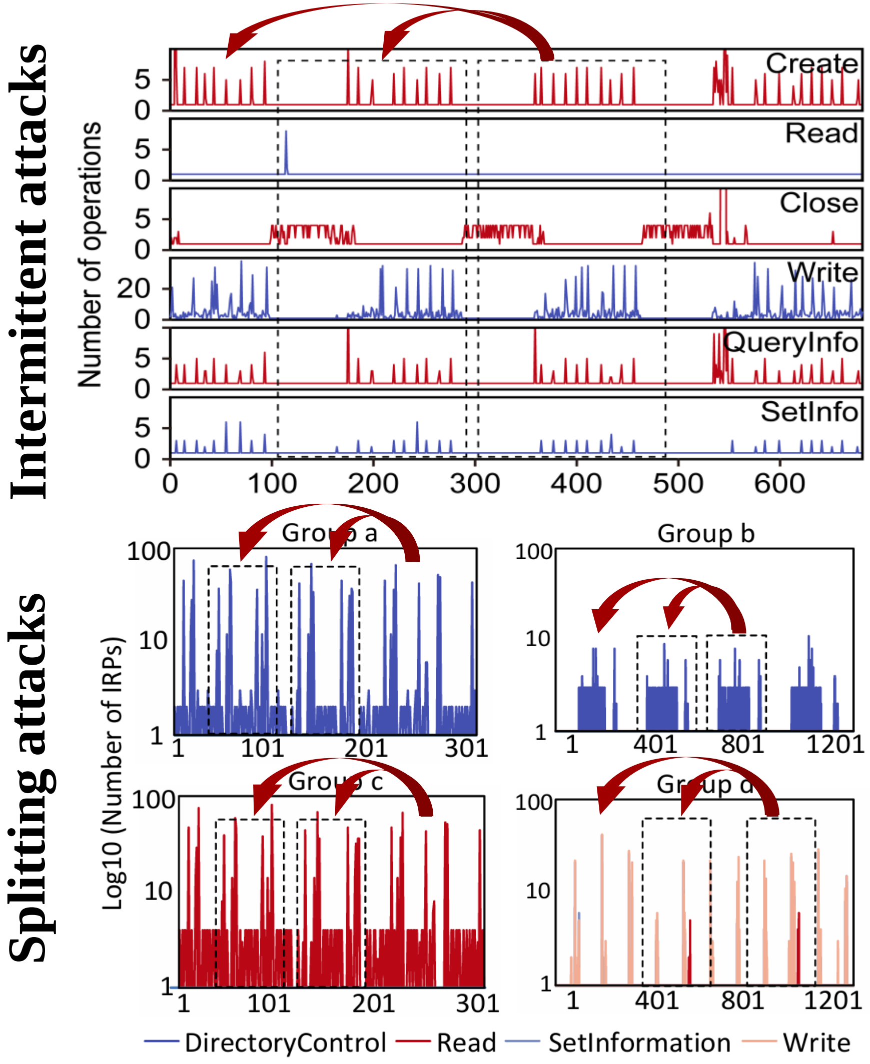
Imitation attacks

Observation:

Step 1: A series of similar behavior segments (①②③)

Step 2: A series of similar operations over a period of time

Observation & Opportunity-1



Observation:

Step 3: Repetitive behavior segments are also observed in splitting attacks and intermittent attacks

Opportunity:

- **Evasive ransomware repetitively executes similar operations based on various templates, which results in its I/O behaviors exhibiting a unique repetitiveness characteristic over the long term**

Observation & Opportunity-2

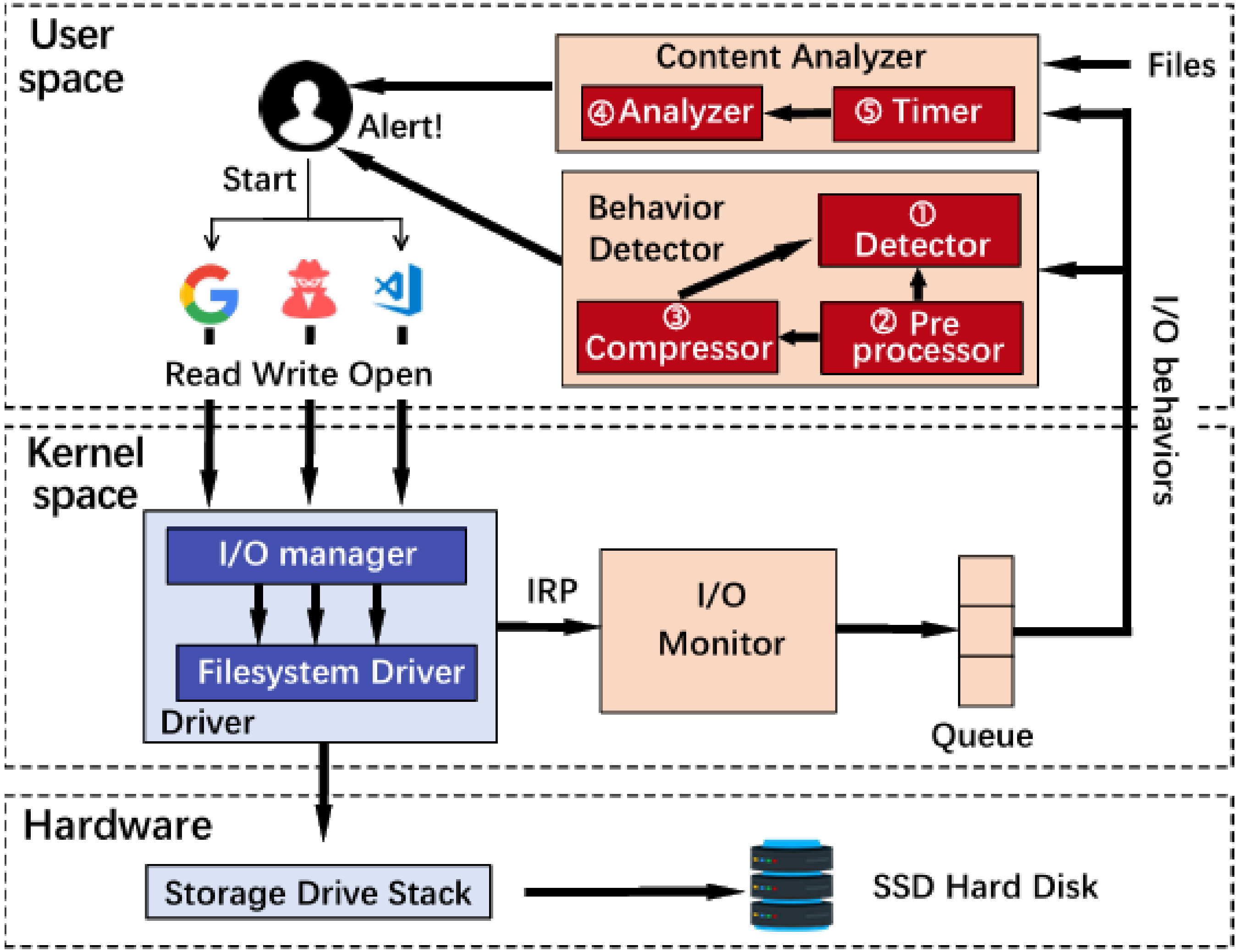
Observation:

- **Step 1: The $\chi 2$ test results can distinguish between encrypted files and benignly modified files to some extent**
- **Step 2: The probability distribution of bytes**
  - **uniform in encrypted files**
  - **slightly fluctuate in files padded with low-entropy data**
  - **exhibit numerous peaks in benignly modified files**

Opportunity:

- **Combining the probability distribution of bytes with the $\chi 2$ test helps distinguish encrypted files more accurately, especially when the differences in the $\chi 2$ test are not significant**

Our approach: ERW-Radar



Component

- ✓ I/O Monitor
- ✓ Behavior Detector
- ✓ Content Analyzer

Function

- ✓ extract behavior information
- ✓ process behavior detection
- ✓ file content analysis

I/O Monitor-Challenge 1

How to extract I/O behaviors？

Challenge 1-1	➢ There are over 30 types of IRPs ➢ The frequency of IRPs reaches up to 3,000/s	➡	**Parsing all IRPs incurs a huge overhead**

I/O Monitor-Challenge 1

How to extract I/O behaviors？

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Challenge 1-2	➢ Behavioral information is extracted in the kernel space ➢ Frequently transmitting it to user space	**Excessive context switching affects system performance**

I/O Monitor-Challenge 1

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Challenge 1-2	➢ Behavioral information is extracted in the kernel space ➢ Frequently transmitting it to user space	Excessive context switching affects system performance

✓ **To alleviate the burden of the system, the key is to reduce the parsed IRPs and the frequency of transmitting data**

I/O Monitor-Solution 1

Lightweight and customized information extraction

- **Parse IRPs that are most relevant to ransomware behaviors**
- **step 1:** Let most IRPs pass through directly except for file-related operations
- **step 2:** Filter out those IRPs with low frequency

I/O Monitor-Solution 1

Lightweight and customized information extraction

◆ **Parse IRPs that are most relevant to ransomware behaviors**

➢ **step 1:** Let most IRPs pass through directly except for file-related operations

➢ **step 2:** Filter out those IRPs with low frequency

◆ **Cache the behavioral information in the queue and send it periodically**

➢ **Eight types of IRPs are retained:**

✓ IRP_MJ_CREATE
✓ IRP_MJ_READ
✓ IRP_MJ_WRITE
✓ IRP_MJ_CLEANUP
✓ IRP_MJ_ QUERY_INFORMATION
✓ IRP_MJ_ SET_INFORMATION
✓ IRP_MJ_ QUERY_VOLUME_INFORMATION
✓ IRP_MJ_ DIRECTORY_CONTROL

➢ **The behavioral information**

✓ Timestamp
✓ Process ID
✓ Type of IRP
✓ Full path of file/directory
✓ Size of write/read buffer

Behavior Detector-Challenge 2

How to detect the behavioral repetitiveness accurately?

Challenge 2-1

System noise

- **repetitive behavior segments are not always entirely consistent**

→ **Rule-based solutions are not feasible (pre-define patterns or features)**

Behavior Detector-Challenge 2

How to detect the behavioral repetitiveness accurately?

Challenge 2-1	**System noise** ➢ **repetitive behavior segments are not always entirely consistent**	➡	**Rule-based solutions are not feasible (pre-define patterns or features)**
Challenge 2-2	**No periodicity** ➢ **intervals of repetitive behavior segments are not always entirely consistent**	➡	**Periodicity-based solutions are not feasible (periodic functions)**

Behavior Detector-Challenge 2

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Challenge 2-2	**No periodicity** ➢ **intervals of repetitive behavior segments are not always entirely consistent**	**Periodicity-based solutions are not feasible (periodic functions)**

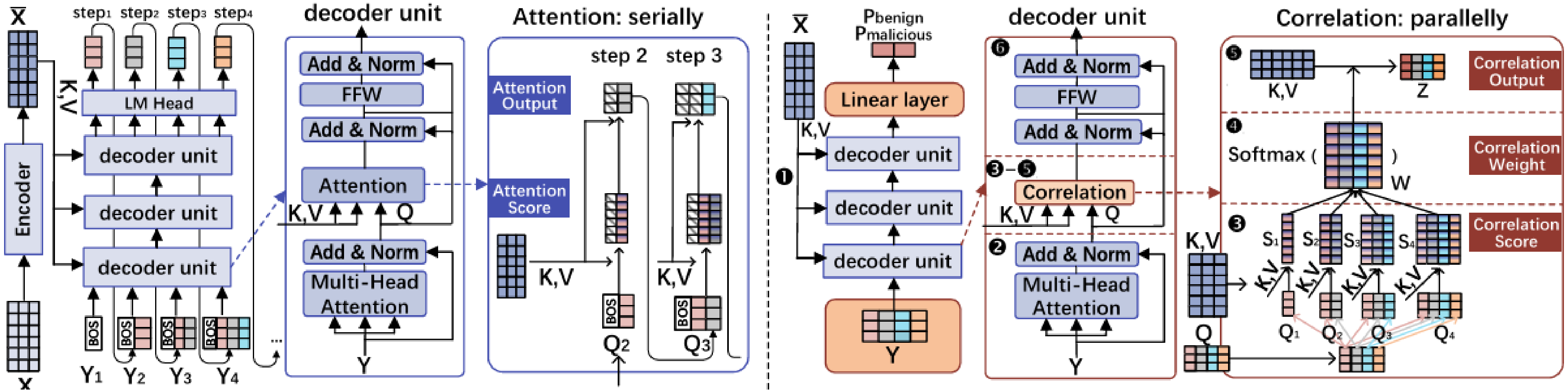
✓ **The recent behavior segments provide precise information about the ongoing operations, the historical ones offer contextual references, their correlation can reflect the behavioral repetitiveness**

Behavior Detector-Solution 2

Correlation mechanism

◆ **Key idea: Context-based detection approach**

- **Step 1:** break down the latest behavior sequence into progressive sub-sequences
- **Step 2:** conduct sequence-wise analysis with historical sequence



Behavior Detector-Challenge 3

How to determine a feasible size for the detection window?

Challenge 3-1	**Short detection window** ➢ **Fail to provide enough contextual information** ➢ **High efficiency**	➡	**Attackers weaken encryption behaviors to evade detection**

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Challenge 3-2	**Long detection window** ➢ **High computational latency** ➢ **More behavior information**	➡	**Cause more file loss**

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✓ **A variable-length detection window can balance detection cost and security guarantees**

Behavior Detector-Solution 3

Dynamic detection windows

◆ **Key idea: Adjust the window size based on recent detection results (idle)**

□ **Case 1: Both behavior detection and content analysis prompt positive results consistently**

- **Inference:** The window size is sufficient to distinguish between malicious and benign behaviors effectively.
- **Approach:** A shorter but more feasible size is probably needed to detect ransomware.

Behavior Detector-Solution 3

Dynamic detection windows

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- **Inference:** The window size is sufficient to distinguish between malicious and benign behaviors effectively.
- **Approach:** A shorter but more feasible size is probably needed to detect ransomware.

□ **Case 2: The two results remain inconsistent**

- **Inference:** The window size is too small, making malicious behaviors hard to identify or resulting in too many FPs.
- **Approach:** Expanding the detection window might capture more contextual information to help identify ransomware accurately.

Content Analyzer-Challenge 4

How to analyze the write buffers of IRPs?

Challenge 4	**In the kernel space** ➢ **Limited computing and storage resources**	➢ **Fail to conduct the χ2 test and probability distribution evaluation** ➢ **Fail to store excessive content for accurate analysis**

Content Analyzer-Challenge 4

How to analyze the write buffers of IRPs?

Challenge 4	**In the kernel space** ➢ **Limited computing and storage resources**	➢ **Fail to conduct the $\chi 2$ test and probability distribution evaluation** ➢ **Fail to store excessive content for accurate analysis**

✓ **Instead of analyzing the write buffers individually, randomly analyzing a series of file segments is more effective in capturing encrypted file content**

Content Analyzer-Solution 4-1

Fine-grained analysis

Insight

- Perform content analysis in user space at the granularity of file segments

Target

- A series of segments with different size from modified files

-the $\chi 2$ test: $\boldsymbol{\sum_{i=0}^{k} \frac{(N_i - E_i)^2}{E_i}, \quad k = 255}$

-the probability: $\boldsymbol{p(i) = \frac{N_i}{L}}$

- $E_i = \frac{L}{256}$
- N_i is the actual number of samples assuming value i
- L is the file content length

Content Analyzer-Solution 4-1

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- N_i is the actual number of samples assuming value i
- L is the file content length

✓ **Compared to entropy value, these features are fine-grained indicators because they consider both the overall randomness and the detailed probability distribution of file content**

Content Analyzer-Solution 4-2

Idle analysis

Insight

- To lessen I/O traffic in a busy system, we can trigger content analysis at idle I/O cycles

Time

- Sustained high intervals between I/O requests imply the arrival of an appropriate analysis time

-I/O Trend: $\frac{x_t+(1-\beta)x_{t-1}+(1-\beta)^2x_{t-2}+\cdots+(1-\beta)^n x_{t-n}}{1+(1-\beta)+(1-\beta)^2+\cdots+(1-\beta)^n}$

- β is the exponential smoothing factor
- x_i is the interval between I/O requests at time i and $i-1$
- n is the number of I/O requests

Content Analyzer-Solution 4-2

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- n is the number of I/O requests

✓ **Given that the latest values of time intervals carry greater weight relative to historical values, I/O Trend is sensitive to reflecting the recent trend of I/O busyness**

Summary of Challenges and Solutions

High overhead of I/O behavior extraction → Lightweight and customized information extraction

Accurate detection of behavioral repetitiveness

Enough contextual information VS. computational latency

Analyze write buffers of IRPs

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Analyze write buffers of IRPs → Fine-grained analysis

Analyze write buffers of IRPs → Idle analysis

Evaluation – Dataset

Evasive	Ransomware	Samples	Traditional	Ransomware	Samples
Family	Number	Rate	Family	Number	Rate
• $ANI^{MSOffice}$ • ANI^{WPS} • ANI^{MSEdge} • $ANI^{Firefox}$ • ANI^{Chrome} • ANI^{WinRAR} • ANI^{7zip} • ANI^{Golang} • ANI^{Rustc} • ANI^{VS}	10	1.10%	Revil Cerber Chaos Darkside Mespinoza Mountlocker Wannacry Xorist HelloXD Virlock	205 201 196 57 24 19 19 9 9 7	22.53% 22.09% 21.54% 6.26% 2.64% 2.09% 2.09% 0.99% 0.99% 0.77%
⋆ $Blackcat$	81	8.90%	Diavol	6	0.66%
⋆ $Blackbasta$	14	1.54%	Karma	5	0.55%
⋆ $Lockfile$	10	1.10%	Voidcrypt	5	0.55%
⋆ $Play$	5	0.55%	Badrabbit	5	0.55%
⋆ $Lockergoga$	5	0.55%	Zepplin	3	0.33%
◇ $Conti$ ◇ $Ryuk$ ◇ $SplittingProto.$	3 2 2	0.33% 0.22% 0.22%	Other 8 families	8	0.88%
Tot. 18 families	132	14.51%	Tot. 23 families	778	85.49%

Ransom Data

- Traditional ransomware
- Evasive ransomware
- Wild samples & prototypes

Benign Data (Common programs)

- Document editing
- Web browsing
- Programming
- Compressing

Evaluation – Performance

Ransomware		ERW-Radar			ERW-Fixed			ERW-Feat			ERW-Trans			ERW-ShieldFS		
	Families	Recall		Overall	Recall		Overall	Recall		Overall	Recall		Overall	Recall		Overall
Imitating	ANI^{MSEdge}	94.25%	Averaged detection recall: **95.23%**	Recall **96.24%** FPR **5.36%** Accuracy **96.65%**	94.03%	Averaged detection recall: 94.85%	Recall 94.98% FPR 6.79% Accuracy 95.54%	69.88%	Averaged detection recall: 79.49%	Recall 88.82% FPR 7.95% Accuracy 88.36%	88.35%	Averaged detection recall: 88.51%	Recall 91.10% FPR 8.79% Accuracy 91.33%	37.38%	Averaged detection recall: 47.58%	Recall 73.85% FPR 8.92% Accuracy 74.49%
	$ANI^{Firefox}$	91.01%			89.39%			64.65%			82.97%			27.21%		
	ANI^{Chrome}	94.21%			93.95%			77.77%			87.03%			42.34%		
	$ANI^{MSOffice}$	97.98%			96.57%			82.98%			90.03%			42.99%		
	ANI^{7zip}	93.79%			94.02%			80.20%			88.87%			50.82%		
	ANI^{WinRAR}	96.94%			96.03%			83.27%			89.79%			44.78%		
	ANI^{VS}	96.33%			95.93%			90.97%			89.96%			74.61%		
	ANI^{Rustc}	97.00%			95.79%			79.38%			88.53%			51.87%		
	ANI^{WPS}	98.33%			97.97%			86.28%			91.07%			56.23%		
Intermittent	Play	96.07%	Averaged detection recall: **97.00%**		94.97%	Averaged detection recall: 95.59%		97.12%	Averaged detection recall: 93.22%		93.00%	Averaged detection recall: 92.21%		89.23%	Averaged detection recall: 77.96%	
	Blackcat	96.84%			94.35%			89.03%			89.13%			70.98%		
	Blackbasta	97.94%			96.44%			96.99%			92.65%			90.85%		
	Lockfile	96.85%			95.33%			87.61%			93.67%			69.63%		
	Lockergoga	97.28%			96.88%			95.36%			92.58%			69.12%		
Splitting	Conti	96.16%	Avg. recall: **96.31%**		94.23%	Avg. recall: 95.36%		90.85%	Avg. recall: 90.76%		91.95%	Avg. recall: 91.80%		86.43%	Avg. recall: 80.31%	
	Ryuk	97.46%			96.75%			92.48%			93.21%			82.57%		
	SplittingProto.	95.30%			95.10%			88.96%			90.25%			71.94%		
*	Tradit. RW	96.12%			94.11%			91.79%			91.89%			89.56%		

- ✓ Compared to ERW-ShieldFS, ERW-Radar increases recall by 6.56% (traditional ransomware) and 27.56% (evasive ransomware)
- ✓ Compared to ERW-Trans, ERW-Radar increases accuracy by 5.32%

Evaluation – Cost

Evasive RW.	Time(ms)	IRPs(Num.)	Files(Num.)	Bytes(KB)	Traditional RW.	Time(ms)	IRPs(Num.)	Files(Num.)	Bytes(KB)
ERW-Radar					ERW-Radar vs. ERW-ShieldFS				
$ANI^{MSOffice}$	383	5	1	4	Badrabbit	370 vs. 290	65 vs. 40	3 vs. 3	67 vs. 42
ANI^{WPS}	392	3	1	3	Darkside	27 vs. 135	1 vs. 27	1 vs. 2	1 vs. 27
ANI^{MSEdge}	690	10	3	9	Diavol	400 vs. 269	963 vs. 599	8 vs. 5	1009 vs. 628
$ANI^{Firefox}$	695	4	1	4	HelloXD	137 vs. 970	1 vs. 175	1 vs. 10	1 vs. 175
ANI^{Chrome}	625	4	1	6	Karma	132 vs. 367	10 vs. 54	1 vs. 3	9 vs. 49
ANI^{WinRAR}	855	10	3	9	Mespinoza	101 vs. 189	34 vs. 67	3 vs. 4	37 vs. 73
ANI^{7zip}	847	120	6	131	Mountlocker	57 vs. 340	18 vs. 79	2 vs. 4	20 vs. 88
ANI^{Golang}	820	45	4	40	Revil	135 vs. 450	5 vs. 98	1 vs. 4	3 vs. 59
ANI^{Rustc}	945	9	3	12	Cerber	104 vs. 378	1 vs. 47	1 vs. 3	1 vs. 47
ANI^{VS}	1918	6	1	12	Virlock	398 vs. 279	890 vs. 563	8 vs. 5	874 vs. 553
Lockergoga	1350	1290	8	1252	Voidcrypt	126 vs. 568	17 vs. 124	2 vs. 5	35 vs. 255
Blackcat [1]	410	17	1(+3)	27(+0.009)	Xorist	1600 vs. 1879	703 vs. 862	11 vs. 16	726 vs. 890
Blackbasta	752	789	6	680	Zeppelin	1536 vs. 2075	693 vs. 839	6 vs. 9	712 vs. 862
Play [1]	260	19	1(+2)	20(+0.006)	Wannacry	121 vs. 561	1 vs. 130	1 vs. 10	1 vs. 130
Lockfile	320	34	2	33	Chaos	79 vs. 138	4 vs. 167	1 vs. 3	2 vs. 84
Conti	475	990	7	1249					
Ryuk	325	895	7	800	others	154 vs. 223	21 vs. 79	2 vs. 3	34 vs. 128
SplittingProto	255	85	2	62					

Evasive ransomware

- Time: 0.68s IRPs: 240.83
- Files: 3.22 Data: 0.24M

Traditional ransomware

- Time: 0.24s IRPs: 149.00
- Files: 2.26 Data: 0.15M

Conclusion

Questions: Evasive ransomware

?? Adjust I/O strategy to make operations less intensive or regular

?? Achieve encryption goal by imitating benign programs

?? Use partial encryption or pad low-entropy data to reduce entropy values

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Our approach: ERW-Radar

✓ **A context-based detector for real-time behavior detection**

✓ **A fine-grained analyzer for file analysis at idle I/O**

✓ **Adaptive strategies to balance accuracy and efficiency**