

| Secret Spilling Drive:

Leaking User Behavior through SSD Contention

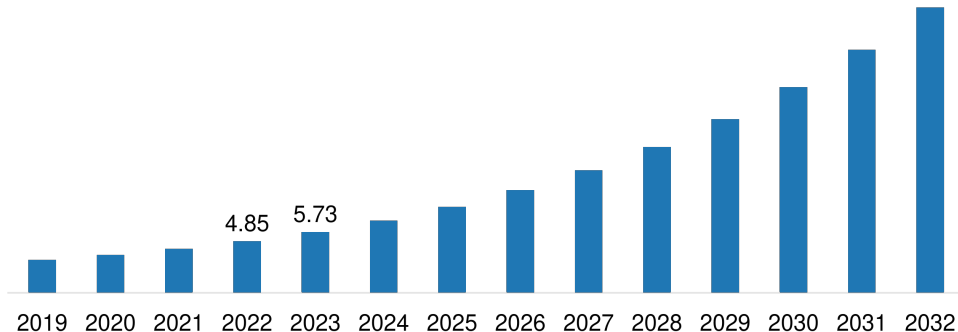
Jonas Juffinger¹ Fabian Rauscher¹ Giuseppe La Manna² Daniel Gruss¹

Graz University of Technology¹, Graz, Austria | Amazon²

NDSS 2025

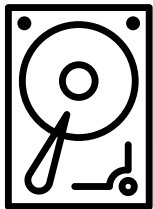
> isec.tugraz.at

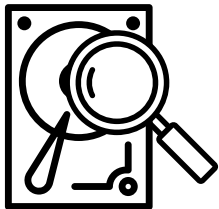
North America Solid State Drive Market Size, 2019-2032 (USD Billion)

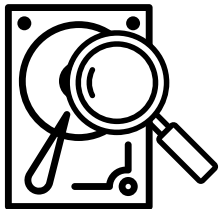


www.fortunebusinessinsights.com [For25]

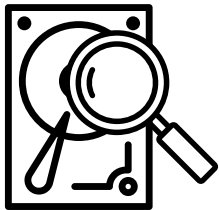
HDD



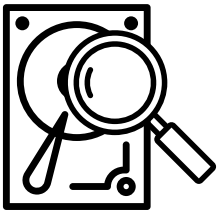




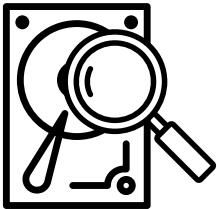
- Disk arm movement [KW91] (1991)
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- Contention [LMS14]
 - 0.1 bit/s covert channel



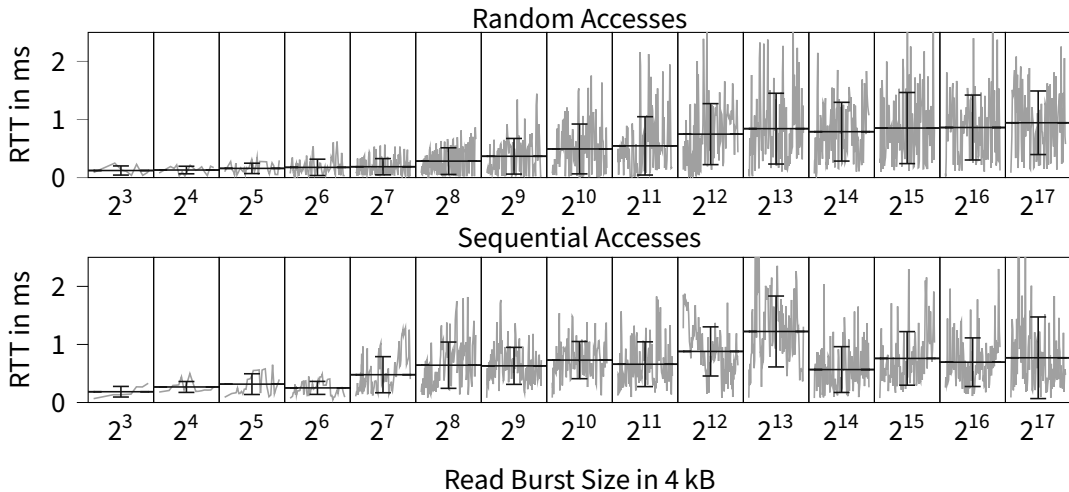
- Disk arm movement [KW91] (1991)
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 - OS and application remote fingerprinting



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 - 0.1 bit/s covert channel
- Emitted Magnetic Radiation [BKS15]
 - OS and application remote fingerprinting
- Emitted Noise [Gur+17]
 - 2 bit/s remote covert channel

What About SSDs?

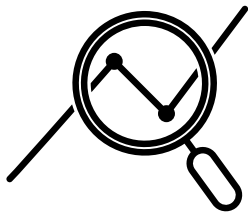
SSD	Model Name	Size	DRAM Cache	PCIe
$\mathcal{A}$	Samsung 980 Pro	256 GB	512 MB LPDDR4	4.0
$\mathcal{B}$	Samsung 980	1 TB	64 MB HMB	3.0
$\mathcal{C}$	Samsung 970 Evo	1 TB	–	3.0
$\mathcal{D}$	Samsung MZVL21T0HCLR-00BL7	1 TB	1 GB LPDDR4	4.0
$\mathcal{E}$	Samsung 970 Evo Plus	2 TB	–	3.0
$\mathcal{F}$	Crucial P5	1 TB	512 MB LPDDR4	4.0
$\mathcal{G}$	Crucial P5 Plus	500 GB	1 GB LPDDR4	4.0
$\mathcal{H}$	Kingston SA2000M81000G	1 TB	1 GB DDR3L	3.0
$\mathcal{I}$	Toshiba KXG6AZNV1T02	1 TB	–	3.0
$\mathcal{J}$	ADATA XPG Gammix S50 Lite	512 GB	512 MB DDR4	4.0
$\mathcal{K}$	Gigabyte Aorus Gen4	500 GB	512 MB DDR4	4.0
$\mathcal{L}$	Western Digital Blue SN550	1 TB	64 MB HMB	3.0



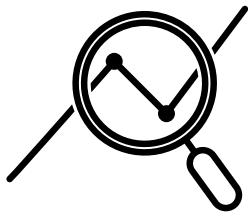
What Can We Detect?

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Two Variables:

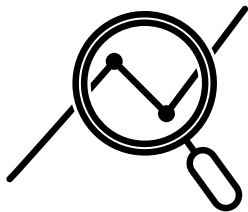


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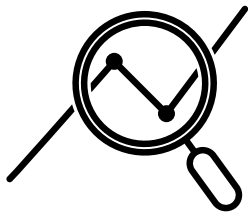


- 1 How much is read from the disk

Two Variables:

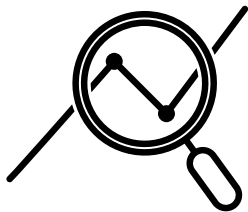


- 1 How much is read from the disk
 - ➔ victim read size



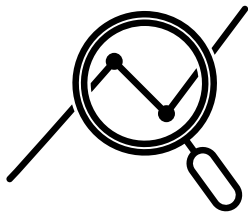
Two Variables:

- 1 How much is read from the disk
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- 2 How often do we measure



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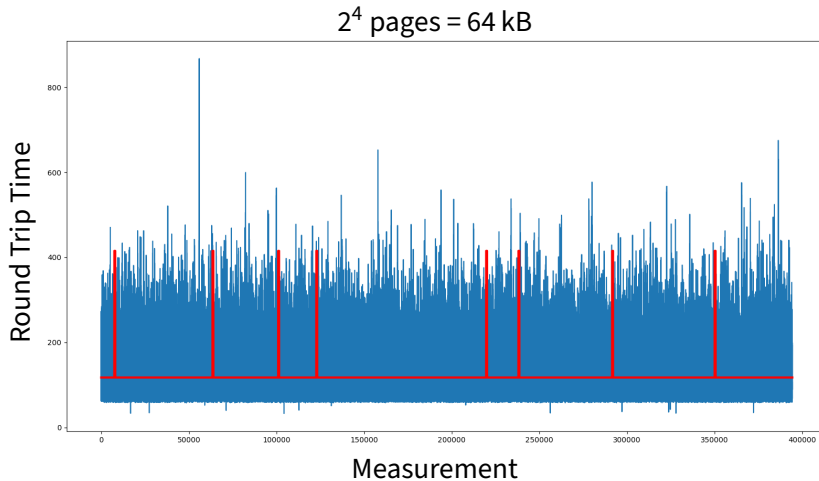
- 1 How much is read from the disk
 - ➔ victim read size
- 2 How often do we measure
 - ➔ observer read delay



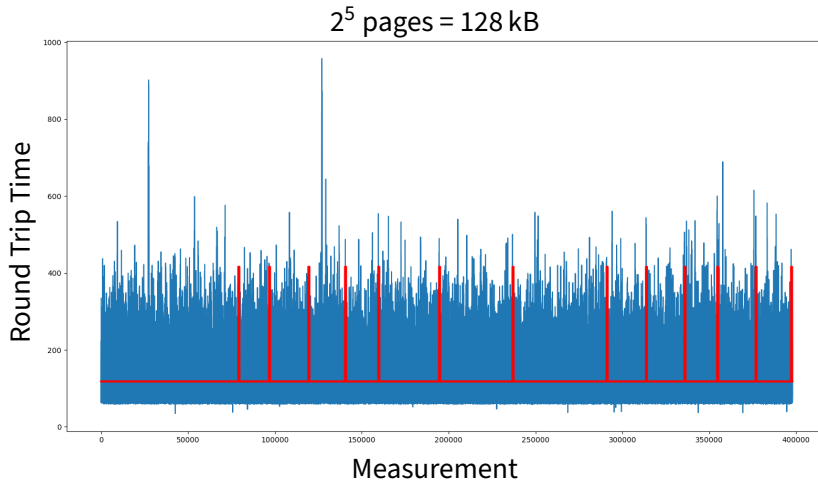
Two Variables:

- 1 How much is read from the disk
 - ➔ victim read size
- 2 How often do we measure
 - ➔ observer read delay
 - ➖ To many measurements create contention

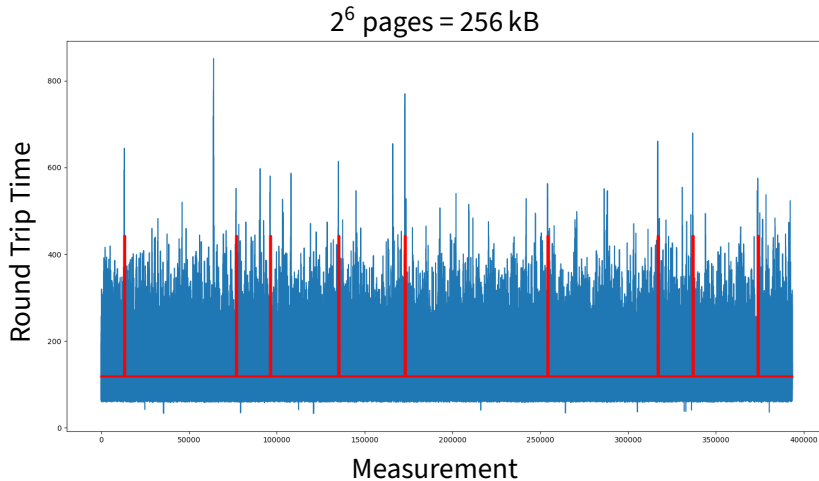
Victim Read Size



Victim Read Size



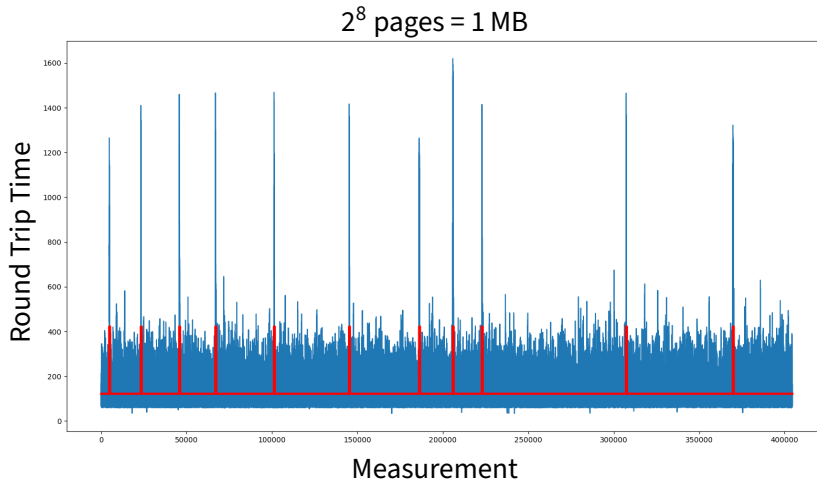
Victim Read Size



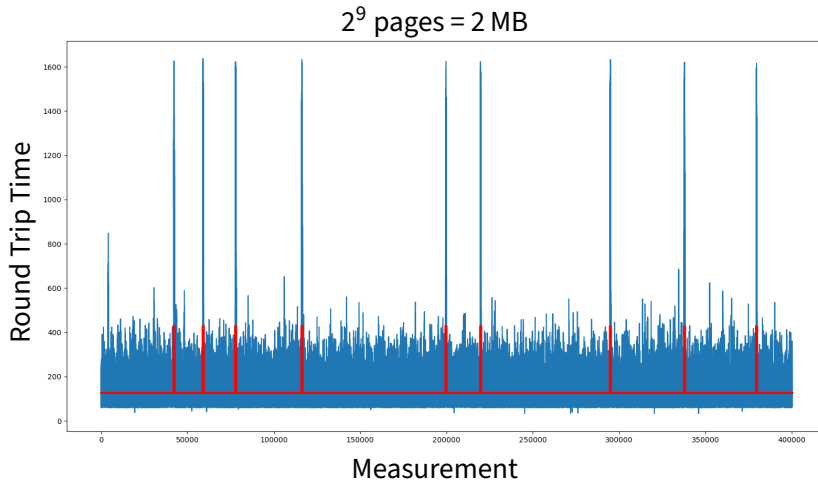
Victim Read Size



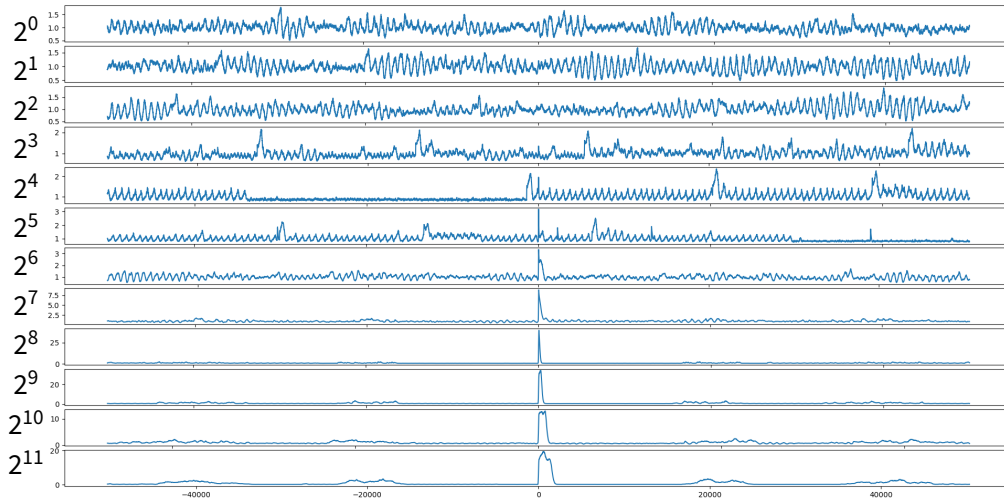
Victim Read Size



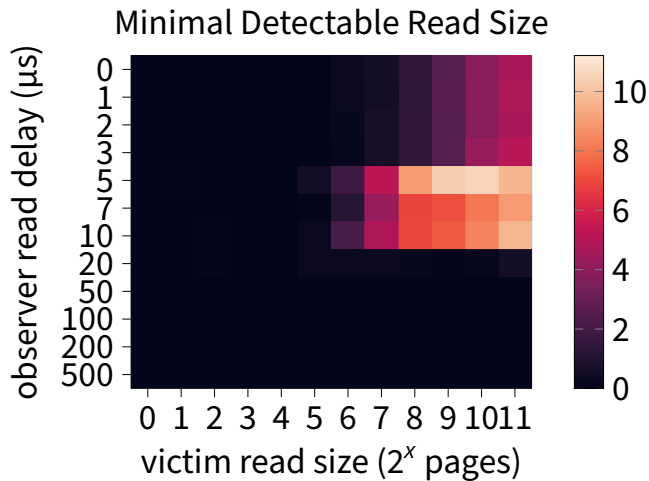
Victim Read Size

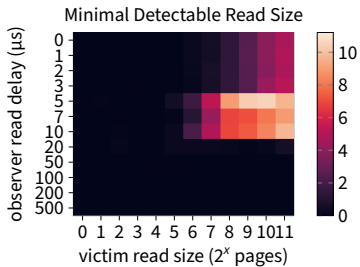
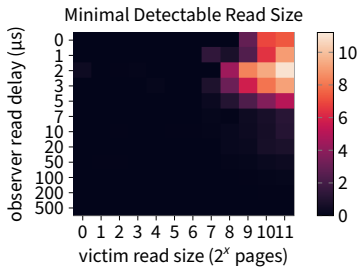
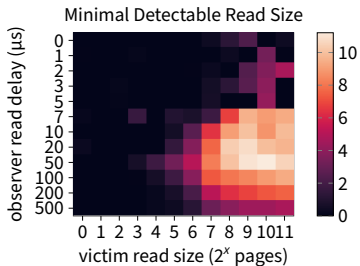
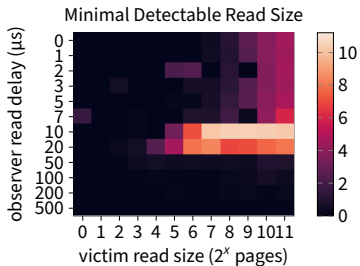


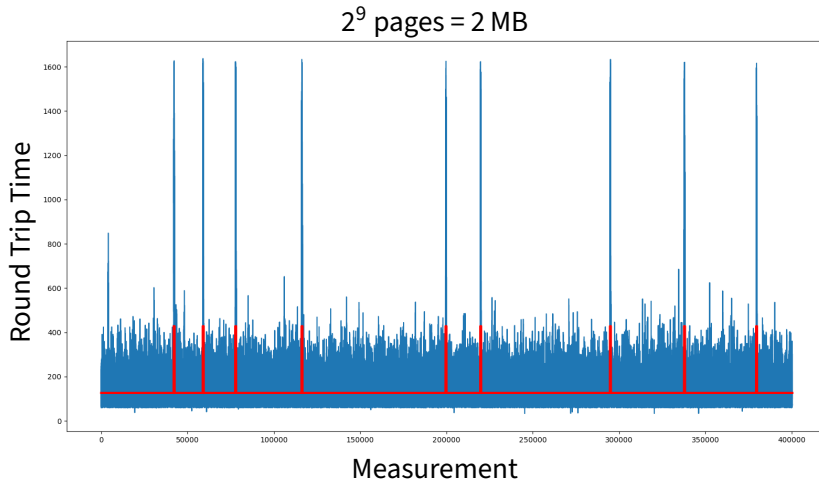
Victim Read Size – Correlation



Minimal Detectable Read Size

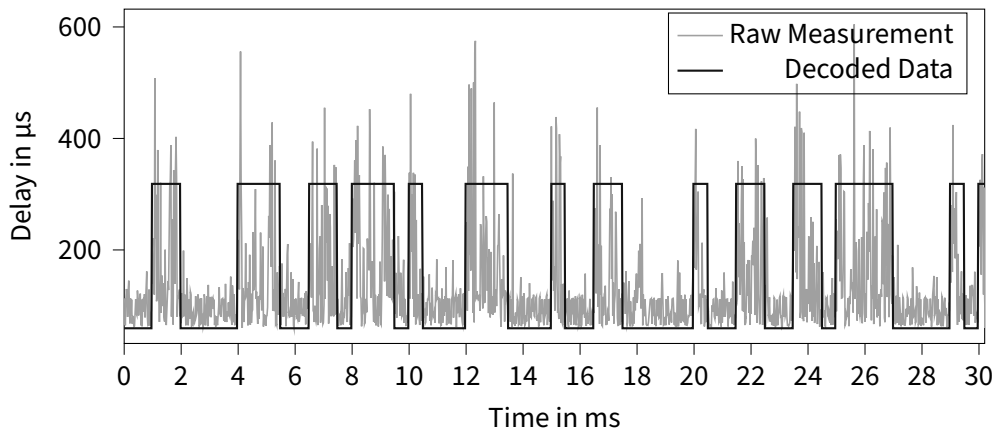


(a) SSD $\mathcal{A}$ (b) SSD $\mathcal{D}$ (c) SSD $\mathcal{H}$ (d) SSD $\mathcal{J}$



Covert Channel

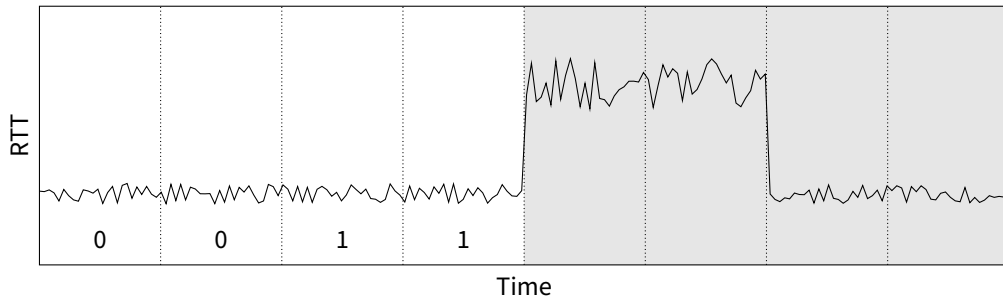
Between Processes and Virtual Machines



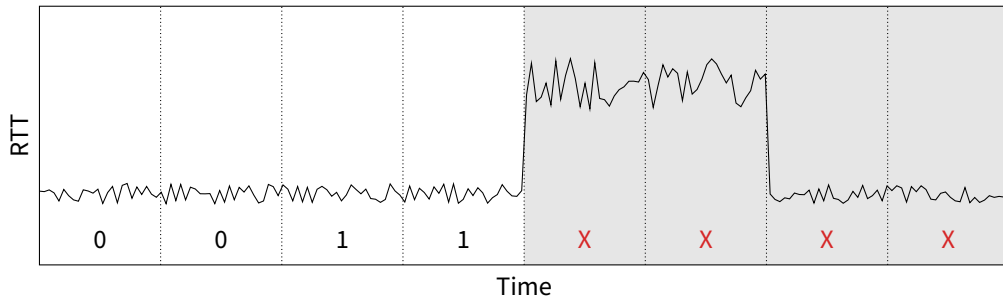
Covert Channel Results

SSD	Process					Virtual Machine				
	1 000 bit/s, $f = 0.12$		Fastest per SSD			500 bit/s, $f = 0.5$		Fastest per SSD		
	Error	Capacity	Trans. Rate	Error	Capacity	Error	Capacity	Trans. Rate	Error	Capacity
$\mathcal{A}$	13.4 %	431 bit/s	2 000 bit/s	14.5 %	808 bit/s	17.9 %	161 bit/s	1 000 bit/s	21.0 %	258 bit/s
$\mathcal{B}$	16.3 %	359 bit/s	2 000 bit/s	14.9 %	787 bit/s	15.4 %	191 bit/s	2 000 bit/s	18.6 %	615 bit/s
$\mathcal{C}$	13.1 %	439 bit/s	5 000 bit/s	19.0 %	1 492 bit/s	15.8 %	186 bit/s	1 000 bit/s	18.8 %	303 bit/s
$\mathcal{D}$	19.6 %	285 bit/s	5 000 bit/s	16.4 %	1 784 bit/s	25.8 %	88 bit/s	1 000 bit/s	29.5 %	124 bit/s
$\mathcal{E}$	13.0 %	441 bit/s	5 000 bit/s	19.4 %	1 447 bit/s	13.3 %	217 bit/s	5 000 bit/s	18.9 %	1 503 bit/s
$\mathcal{F}$	17.4 %	333 bit/s	2 000 bit/s	17.5 %	660 bit/s	13.7 %	212 bit/s	1 000 bit/s	14.5 %	404 bit/s
$\mathcal{G}$	15.6 %	375 bit/s	2 000 bit/s	14.3 %	814 bit/s	18.2 %	158 bit/s	2 000 bit/s	18.8 %	605 bit/s
$\mathcal{H}$	25.0 %	188 bit/s	2 000 bit/s	24.2 %	403 bit/s	14.0 %	207 bit/s	2 000 bit/s	21.6 %	493 bit/s
$\mathcal{I}$	13.5 %	428 bit/s	2 000 bit/s	17.5 %	664 bit/s	19.4 %	145 bit/s	1 000 bit/s	21.0 %	258 bit/s
$\mathcal{J}$	13.2 %	437 bit/s	2 000 bit/s	17.8 %	647 bit/s	14.9 %	196 bit/s	2 000 bit/s	19.1 %	592 bit/s
$\mathcal{K}$	29.2 %	129 bit/s	2 000 bit/s	15.5 %	755 bit/s	14.6 %	200 bit/s	2 000 bit/s	16.6 %	702 bit/s
$\mathcal{L}$	13.1 %	439 bit/s	5 000 bit/s	20.8 %	1 313 bit/s	15.1 %	194 bit/s	1 000 bit/s	13.5 %	429 bit/s
Avg	16.9 %	357 bit/s	3 000 bit/s	17.7 %	964 bit/s	16.5 %	180 bit/s	1 750 bit/s	19.3 %	524 bit/s

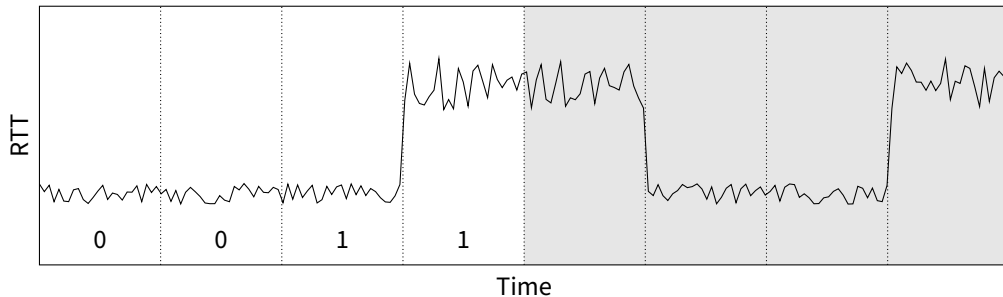
Threshold Detection



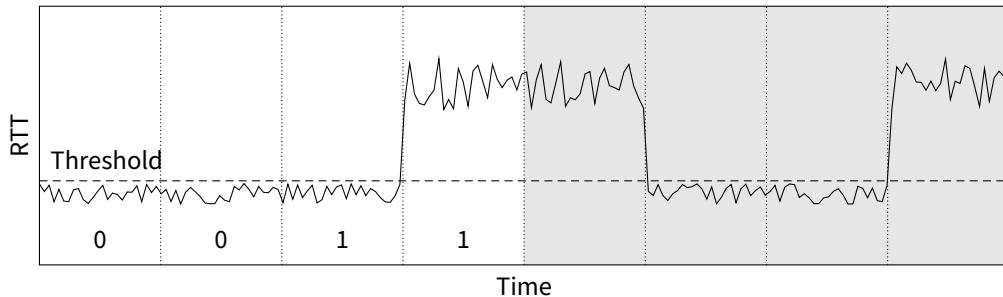
Threshold Detection



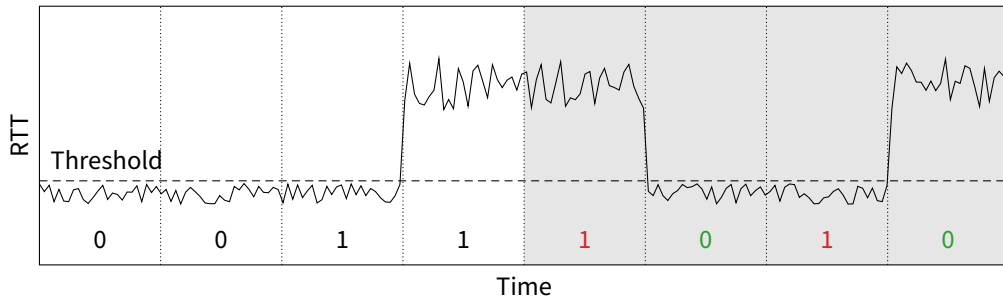
Threshold Detection



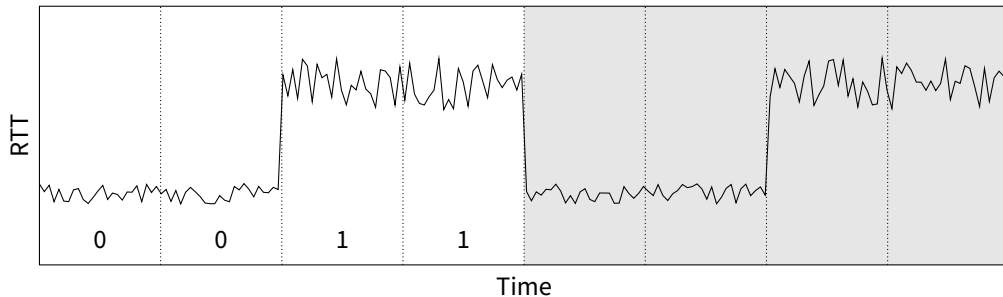
Threshold Detection



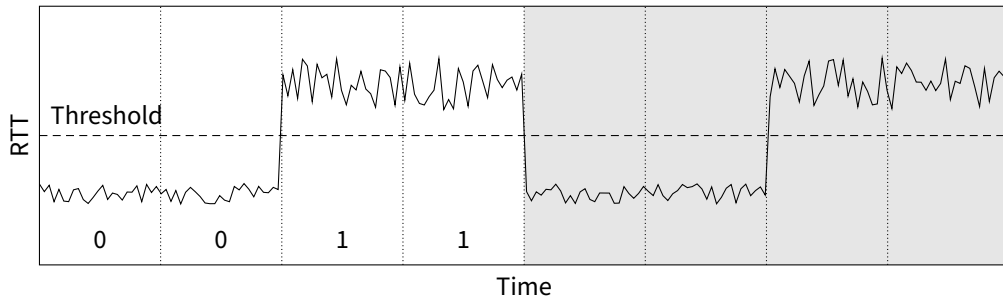
Threshold Detection



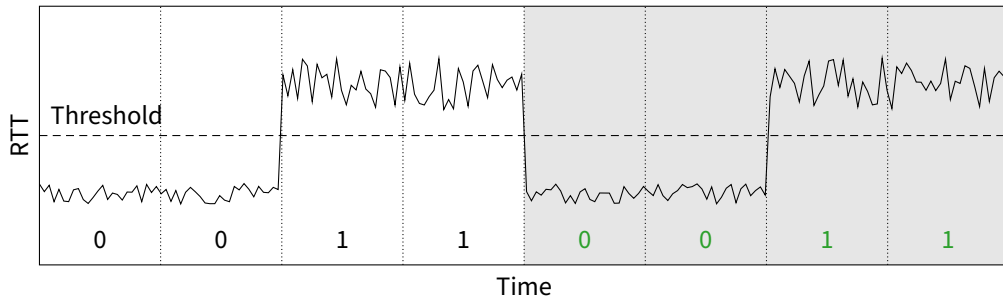
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Threshold Detection



Threshold Detection



Covert Channel Results - Process

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Covert Channel Results - Virtual Machine

SSD	500 bit/s, $f = 0.5$		Fastest per SSD		
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$\mathcal{A}$	17.9 %	161 bit/s	1 000 bit/s	21.0 %	258 bit/s
$\mathcal{B}$	15.4 %	191 bit/s	2 000 bit/s	18.6 %	615 bit/s
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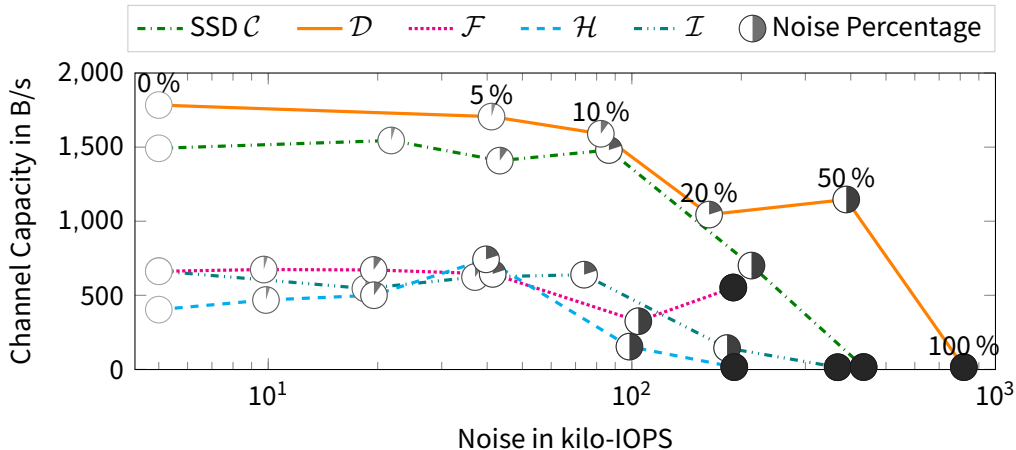
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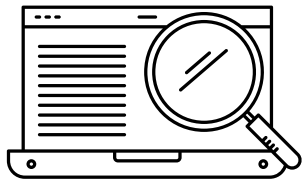
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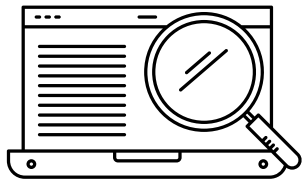
Noise Impact



Website Fingerprinting

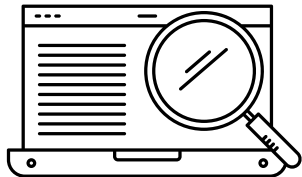


Identify websites currently opened on the same machine.



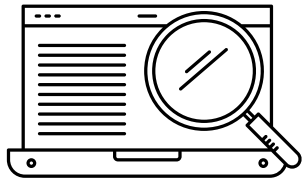
Identify websites currently opened on the same machine.

- Web browsers cache assets on the disk



Identify websites currently opened on the same machine.

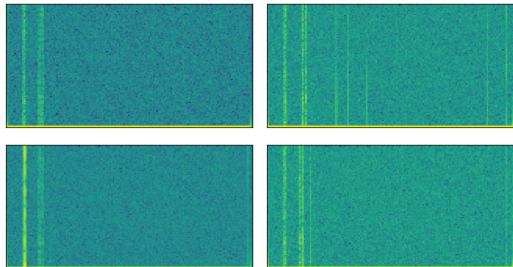
- Web browsers cache assets on the disk
- They are read from the disk on each load



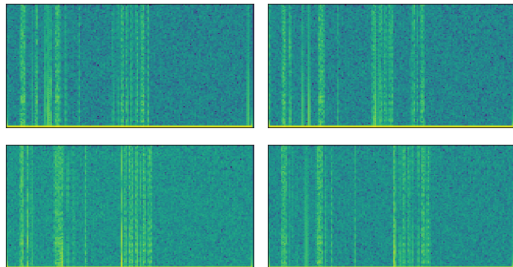
Identify websites currently opened on the same machine.

- Web browsers cache assets on the disk
- They are read from the disk on each load
- Create a unique fingerprint

Website Spectrograms

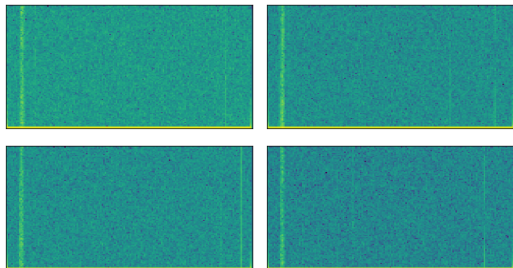


(a) google.com

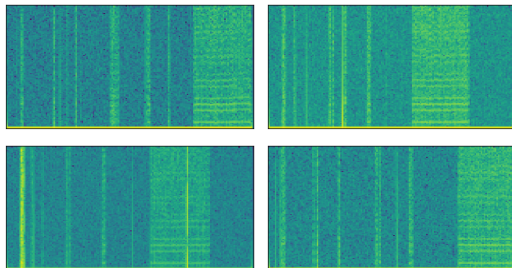


(b) youtube.com

Website Spectrograms

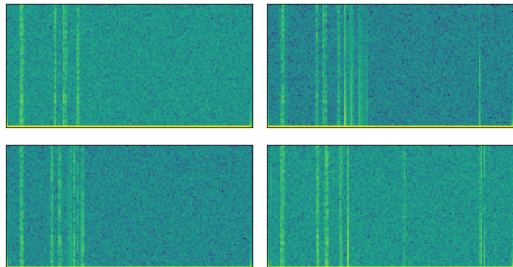


(c) facebook.com

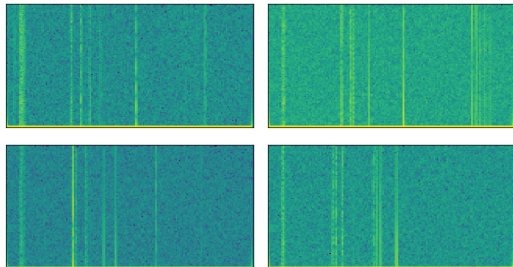


(d) qq.com

Website Spectrograms

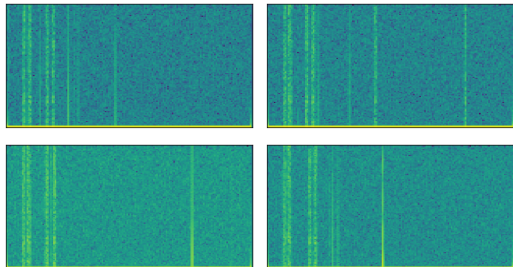


(e) xhamster.com

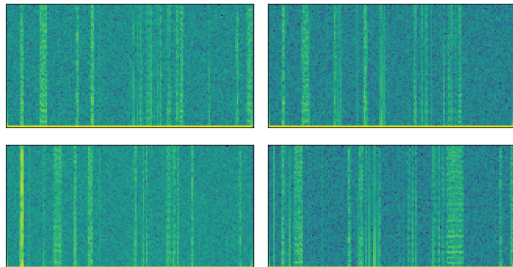


(f) imdb.com

Website Spectrograms

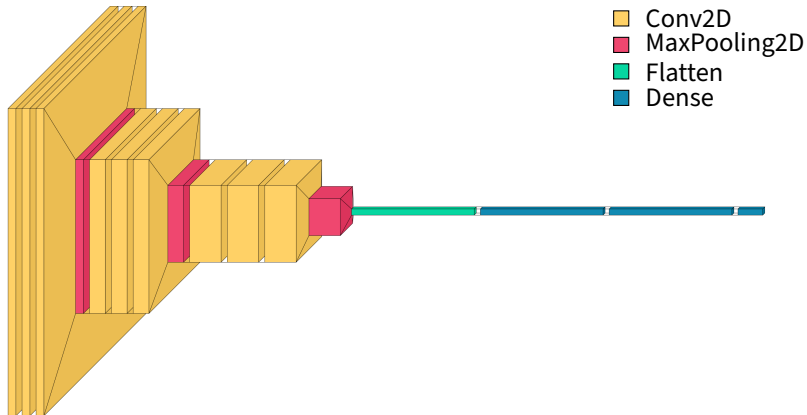


(g) force.com

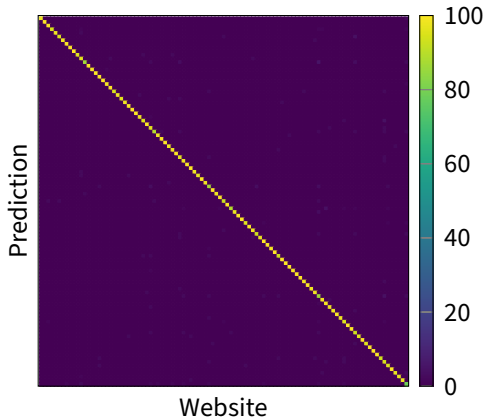


(h) dropbox.com

Convolutional Neural Network



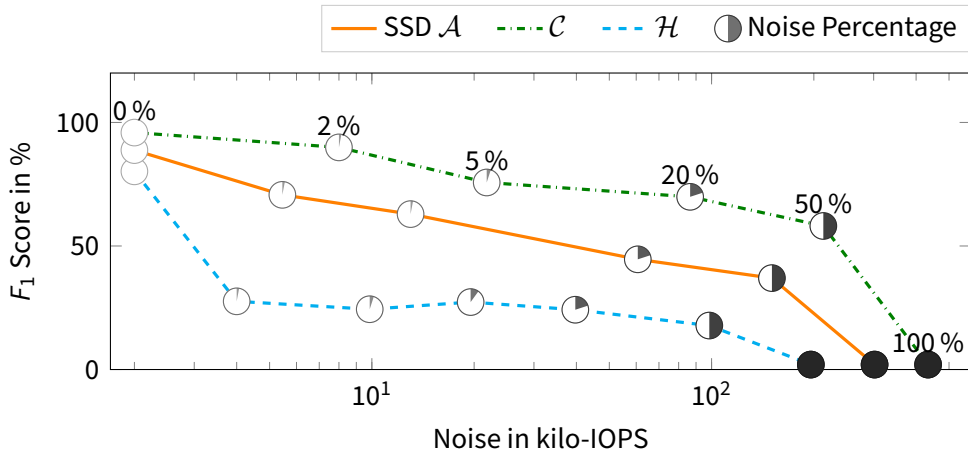
Website Fingerprinting - Results



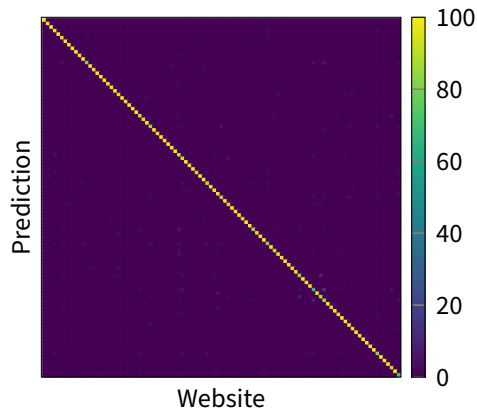
100 Websites + Open World Dataset

SSD	DRAM Cache	PCIe	Accuracy ↓
Crucial P5	✓	4.0	97.0 %
Gigabyte Aorus Gen4	✓	4.0	97.0 %
Samsung 970 Evo Plus	✗	3.0	96.6 %
...			
ADATA XPG Gammix S50 Lite	✓	4.0	88.7 %
Kingston SA2000M81000G	✓	3.0	80.2 %

Noise Impact

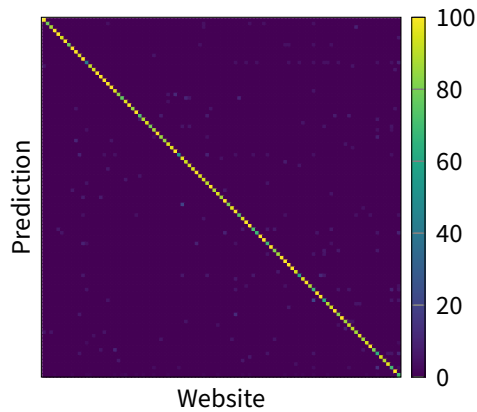


Noise Impact - Heatmap - SSD $\mathcal{C}$



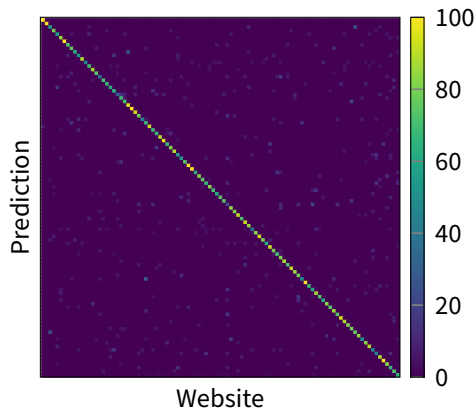
0 % Noise – 95.9 %

Noise Impact - Heatmap - SSD $\mathcal{C}$



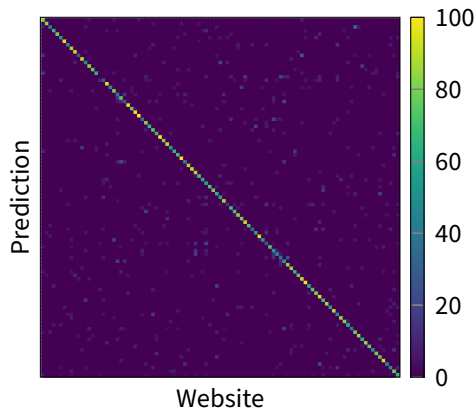
2 % Noise – 89.9 %

Noise Impact - Heatmap - SSD $\mathcal{C}$



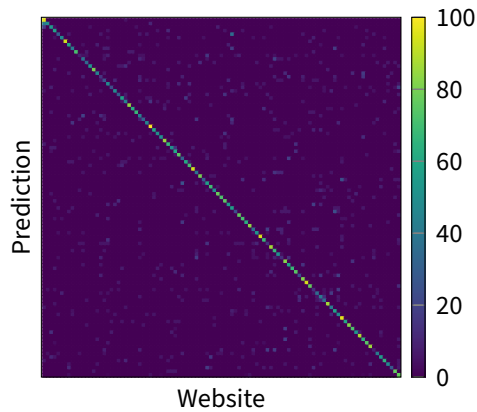
5 % Noise – 75.7 %

Noise Impact - Heatmap - SSD $\mathcal{C}$



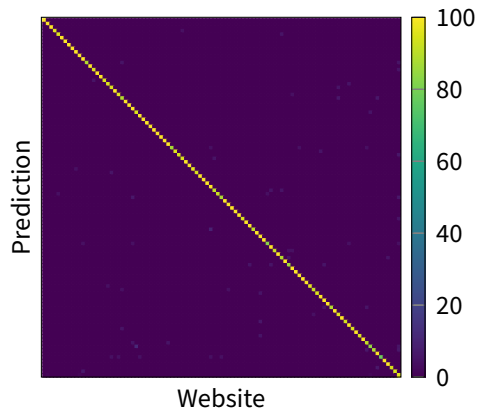
20 % Noise – 69.9 %

Noise Impact - Heatmap - SSD $\mathcal{C}$



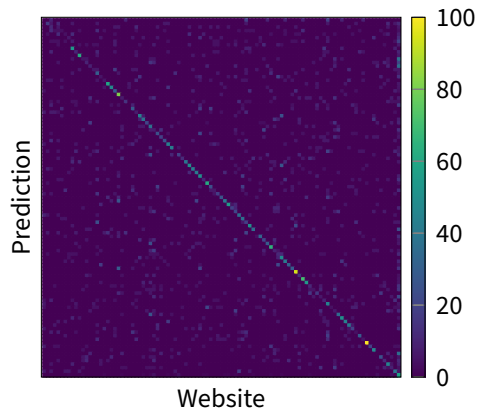
50 % Noise – 58.1 %

Noise Impact - Heatmap - SSD $\mathcal{H}$



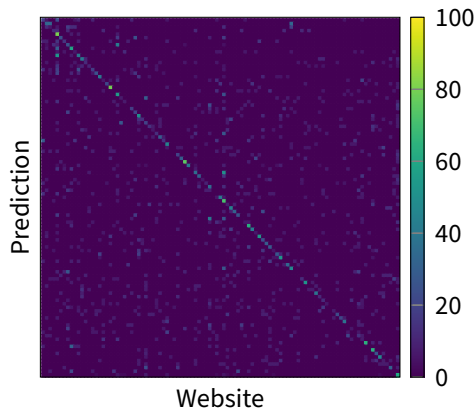
0 % Noise – 80.2 %

Noise Impact - Heatmap - SSD $\mathcal{H}$



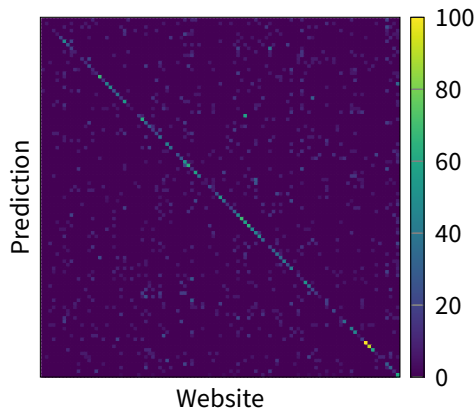
2 % Noise – 27.6 %

Noise Impact - Heatmap - SSD $\mathcal{H}$



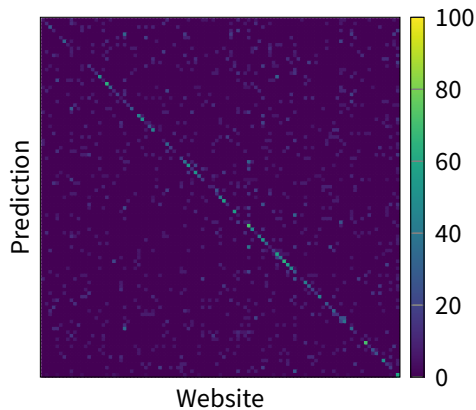
5 % Noise – 24.4 %

Noise Impact - Heatmap - SSD $\mathcal{H}$



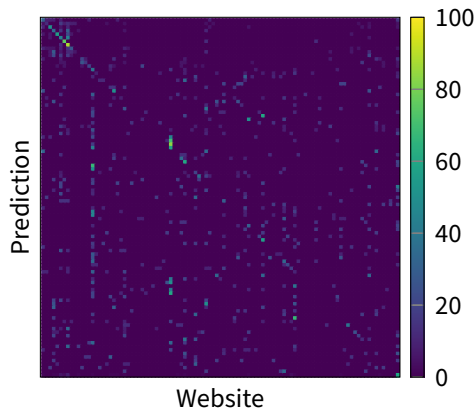
10 % Noise – 27.3 %

Noise Impact - Heatmap - SSD $\mathcal{H}$

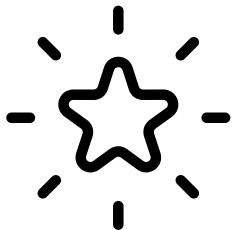


20 % Noise – 24.2 %

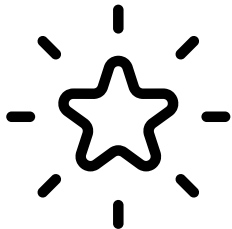
Noise Impact - Heatmap - SSD $\mathcal{H}$



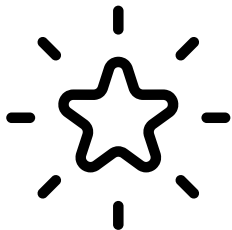
50 % Noise – 17.8 %



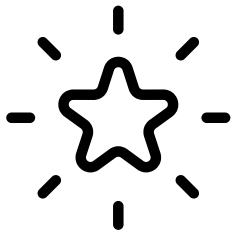
- High IOPS do **not** protect against contention



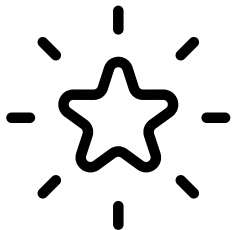
- High IOPS do **not** protect against contention
- They **enable** a high bandwidth side channel



- High IOPS do **not** protect against contention
- They **enable** a high bandwidth side channel
- **Covert Channel** with up to 1.8 kbit/s



- High IOPS do **not** protect against contention
- They **enable** a high bandwidth side channel
- **Covert Channel** with up to 1.8 kbit/s
- **Website Fingerprinting** with up to 97 % accuracy



- High IOPS do **not** protect against contention
- They **enable** a high bandwidth side channel
- **Covert Channel** with up to 1.8 kbit/s
- **Website Fingerprinting** with up to 97 % accuracy
- **Difficult** to mitigate

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Der Wissenschaftsfonds.



Der Wissenschaftsfonds.

DFG Deutsche
Forschungsgemeinschaft



Red Hat



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| Secret Spilling Drive:

Leaking User Behavior through SSD Contention

Jonas Juffinger¹ Fabian Rauscher¹ Giuseppe La Manna² Daniel Gruss¹

Graz University of Technology¹, Graz, Austria | Amazon²

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> isec.tugraz.at

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