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Enabling Privacy-Aware Zone Exchanges Among Authoritative and Recursive DNS Servers

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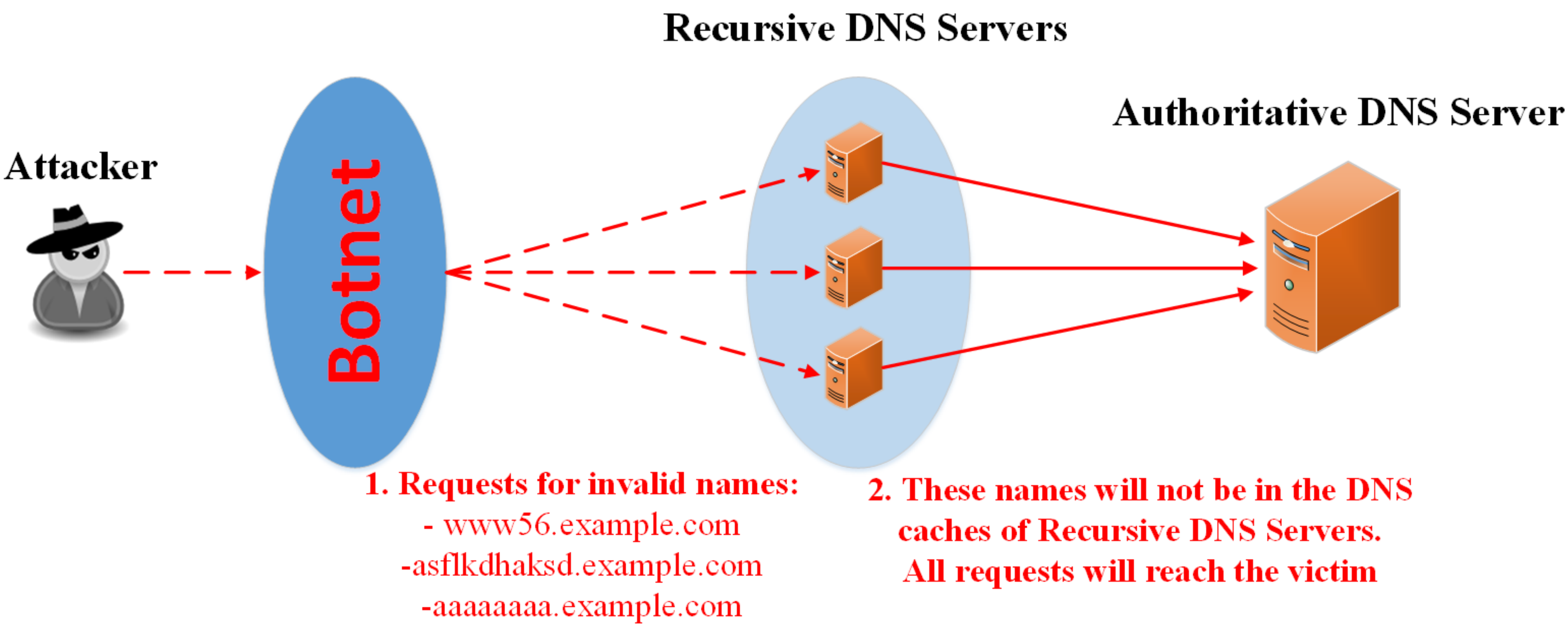
Motivation: DNS Water Torture Attacks



- DDoS attacks can be mitigated more efficiently close to their origins

  Our use case for DNS: *Scrubbing services*, *Recursive DNS Server* Filters

- **However**, *AXFR* requests are typically restricted for security reasons

Contribution

- A privacy-aware schema for the efficient distribution of *Authoritative DNS Server* zones to *Recursive DNS Servers* or *scrubbing services*

- ***Design Requirements***:
  → ***Privacy-aware zone distribution***
  → ***Efficient zone mapping*** (storage, filtering latency, consumed bandwidth)
  → ***Compatibility with the existing DNS infrastructure*** (*AXFR*, *IXFR* requests)
  → ***Support for incremental updates***

- Relying on ***probabilistic data structures*** as datastores for valid *Authoritative DNS Server* zone names. These fulfill the previous design requirements.

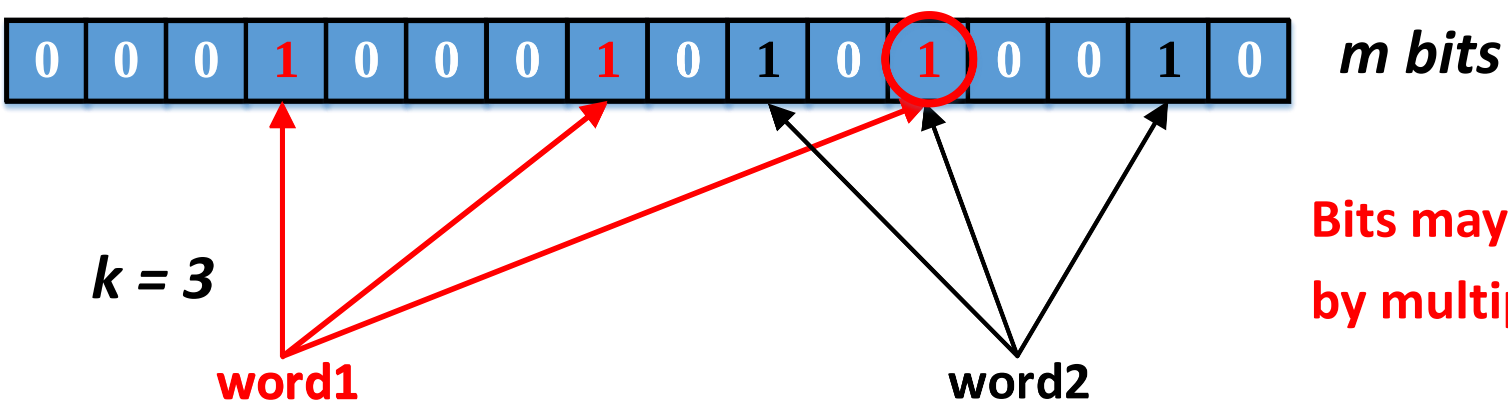
- Extending previous work (***IEEE CloudNet 2019***):
  Bloom Filters were used to map the names of large DNS zones and filter suspicious DNS traffic in cloud infrastructures
  → In this paper, we implement the zone distribution mechanism
  → Instead of ***Bloom Filters***, we use ***Cuckoo Filters*** that support item deletion

Background: Bloom Filters

- **Bitarrays** (of ***m*** bits) used for
  Approximate Membership Lookups:

  Is element *x* stored in the *Bloom Filter*?

- All bits are initially set to 0.
  Each element is hashed with ***k*** different *hash functions*.
  Corresponding positions (***hash results mod m***) are set to 1.



Bits may be shared by multiple items

False Negatives (Item in the filter, lookup says it is not): Impossible
False Positives (Item not in the filter, lookup says it is): Possible

Bloom Filter based Approaches for DNS

- **Related approaches:**
  - Mapping DNSSEC zone names to accelerate authenticated responses
  - Logging DNS data
  - Detecting botnet traffic
  - Tracking newly observed domain names

Privacy-aware approaches, but **deletions are not supported**

Cuckoo Filters **vs** ***Bloom Filters*****:**

→ *Cuckoo Filters* are more time and space efficient

→ *Cuckoo Filters* support element deletion

Background: Cuckoo Filters

- Elements are inserted as fingerprints in entries of a 2D array
  - Fingerprints of size ***f*** bits are calculated using the function *fgp*()
- ***Cuckoo Filters* are characterized by:**
  - Number of available buckets ***m***
  - Fingerprint entries ***b*** per bucket

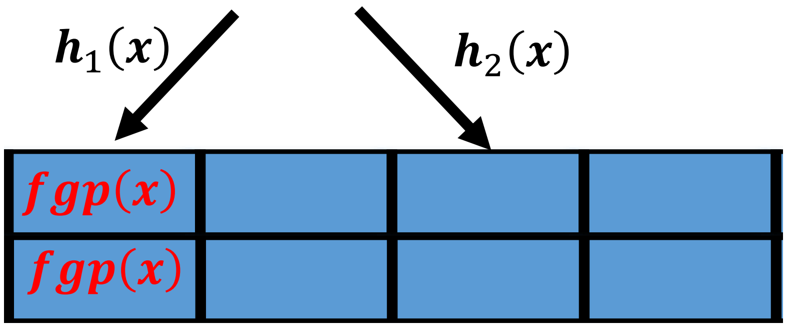
Partial-Key Cuckoo Hashing Technique

- Each element ***x*** is assigned a pair of buckets h_1 and h_2:

$$\begin{cases} h_1(x) = hash(x) \\ h_2(x) = h_1(x) \oplus hash(fgp(x)) \end{cases}$$

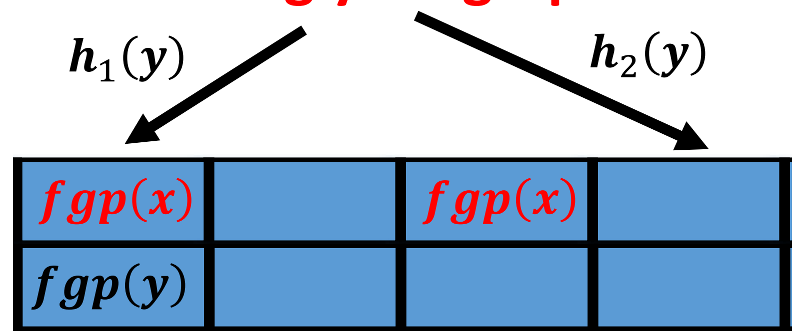
- **Example for m=4, b=2:**

Inserting x' fingerprint 2 times



One of the two buckets is randomly selected

Inserting y' fingerprint



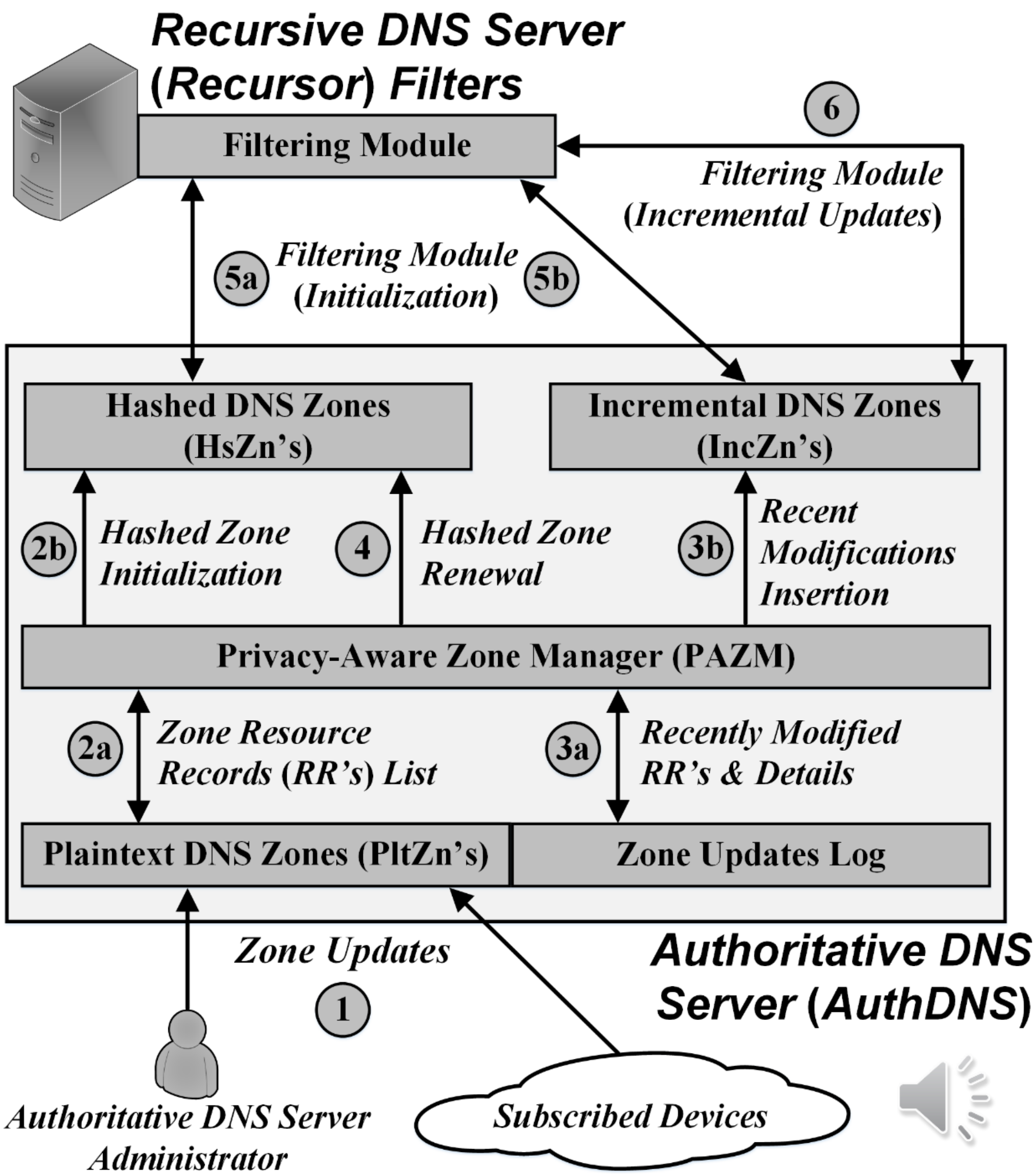
***fgp*(*x*) evicted to alternate bucket**

***x* and *y* share a bucket**

Network Management & Optimal Design Laboratory

Baseline Design

- ***Privacy-Aware Zone Manager***
- ***Hashed DNS Zones***
- ***Incremental DNS Zones***



Implementation: The Privacy-Aware Zone Manager

Builds and maintains the *Cuckoo Filters* whose fingerprints are used to create and revise the privacy-aware DNS zones

Actions:

- Retrieves *Plaintext DNS Zone RR*'s, hashes their *FQDN* into fingerprints, creates *Cuckoo Filters* and the *Hashed DNS Zones*
- Retrieves *Plaintext DNS Zone* changes regularly, updates the in-memory *Cuckoo Filters* and the *Incremental DNS Zones*
- Ignores *RR*'s whose value was updated, but their *FQDN* did not change
- Special treatment for *RR*'s that share *FQDN*'s with others, but differ in *RR* type and/or value (usage of frequency counters)

- Implemented in ***Python 3***

- ***Murmurhash3*** for *fingerprint* and *hash* calculations

Implementation: Hashed DNS Zones (1)

These zones hold the *FQDN*'s of the *Plaintext DNS Zones* hashed and mapped in *Cuckoo Filters* (***Use of AXFR***)

Serialization format (zone *hszn.tld*):

```
; Zone: hszn.tld
; Cuckoo Filter Parameters
buckets.hszn.tld      IN   TXT   <m>
entries.hszn.tld      IN   TXT   <b>
fgp-size.hszn.tld     IN   TXT   <f>
fgp-algo.hszn.tld     IN   TXT   <fgp()>
hash-algo.hszn.tld    IN   TXT   <hash()>
; Cuckoo Filter Data
<n>.hszn.tld          IN   TXT   <RR Data>
```

Cuckoo Filter parameters & algorithms:

- Number of buckets ***m***, fingerprint size ***f***, number of entries ***b***
- Algorithms used for fingerprint and candidate buckets calculation

Implementation: Hashed DNS Zones (2)

Example for the 1st data RR of the ***.ntua.gr*** *Hashed DNS Zone*

***Cuckoo Filter* with:**

- ***f***=12 bit fingerprints
- ***b***=4 entries / bucket
- 82 fingerprints mapped

```
0.hszn.tld    IN    TXT    "c64.1dd4d1d590bfbf3ddaa20
3f6cb764b2c647a7063faff67fac8811df81c0fbe65f2.a5a.de2
bcd4666b6f10ba60e5cdc824ee3ba1807bd26d08a3.745a2f8
9e.395cbb723310f27e51c28ee3a96ad2e788092d2514513.44
33be06ed3314bc570ce85c921f5a59e07ee8db11.5f766e444e
96504eb01d090cc0d445.3eb."
```

Rules:

- Equally sized fingerprints of $[f/4]$ Bytes (hex digits).
- Fingerprints requiring less than $[f/4]$ Bytes are prepended with 0's
- The fingerprints of multiple *Cuckoo Filter* buckets are mapped sequentially within a single *TXT* type *RR*
- Buckets with vacant entries require a trailing dot as they do not have explicit boundaries. Full buckets do not.
- *TXT* type *RR* limit: 255 Bytes

Implementation: Incremental DNS Zones

They map name changes of *Plaintext DNS Zones* (***Use of IXFR***)

Serialization format (zone inczn.tld):

```
; Zone: inczn.tld
; Zone Parameters
last-serial.inczn.tld    IN    TXT    <serial>
sequence.inczn.tld       IN    TXT    <seq-no>
; Updates
<n>.inczn.tld  IN  TXT  "<fgp> <action> <h1>,<h2>"
```

Rules:

- ***last-serial***: Changes prior to this value are incorporated in the *Hashed DNS Zones*. Starting point for *Recursive DNS Servers* to begin retrieving data from an *Incremental DNS Zone*
- ***sequence***: Defines if *a Hashed DNS Zone* is stale and must be downloaded again, e.g. when *Cuckoo Filter* parameters change
- ***Updates***: The fingerprint of the name that changed, action (name added/deleted) and buckets of the fingerprint in the *Cuckoo Filter*

Evaluation: Testbed & Dataset

Testbed:

- ***Authoritative DNS Server***: VM with 2 vCPUs, 16 GB RAM
- ***DNS Software***: *BIND9*

Available DNS Zones:

- ***.ntua.gr***: 8,294 distinct *FQDN*'s
- ***.su***: 109,719 distinct *FQDN*'s
- ***.se***: 1,387,690 distinct *FQDN*'s
- ***.ru***: 5,325,231 distinct *FQDN*'s

Hashed DNS Zones Privacy-Awareness

Cuckoo Filters store names hashed, **but** attackers may attempt to gain insight into zone contents by performing brute force attacks

Target: Assess the capabilities of *Cuckoo Filters* to withstand brute force attacks in the context of DNS

Evaluation of ***True Positives*** (***TP's***) and ***False Positives*** (***FP's***) looking up all permitted name combinations with 1st label length of 3-7 chars

1st Label Length (Characters)	*TP's* (*FQDN's*)	*FP's* (*FQDN's*)	*FP's/TP's* (Ratio)
3	320	57	0.18
4	640	1,789	2.80
5	1,178	68,296	57.98
6	1,183	2,532,293	2,140.57
7	1,363	93,665,989	68,720.46

- *Zone*: ntua.gr
- *FP ratio*: 0.3%
- 37 possible characters (letters, digits, hyphen)

- ***FQDN*'s with 1st label longer than 5 chars protected with high certainty**
- **Longer 1st labels result into more *False Positives***

Hashed DNS Zones Serialization

Target: Determine the applicability of diverse data serialization formats for mapping zone names into *Hashed DNS Zones*

Considered serialization formats:

- *Cuckoo Filter* with multiple buckets mapped within each *RR*
- *Cuckoo Filter* with a single bucket mapped within each *RR*
- *Bloom Filter* with multiple Bytes mapped within each *RR*

Bandwidth consumption during an AXFR request:

Indicative Zone (Distinct *FQDN's*)	Information Serialization Format			*Cuckoo Filters* (Actual Size)
	Cuckoo Filter (Multiple Buckets / *RR*)	*Cuckoo Filter* (Single Bucket / *RR*)	*Bloom Filter* (Multiple Bytes / *RR*)	
ntua.gr (8,294)	26.77 KB	63.91 KB	41.86 KB	13.51 KB
su (109,719)	352.1 KB	876.1 KB	553.11 KB	178.58 KB
se (1,387,690)	4.36 MB	11.21 MB	6.86 MB	2.21 MB
ru (5,325,231)	16.78 MB	43.76 MB	26.34 MB	8.46 MB

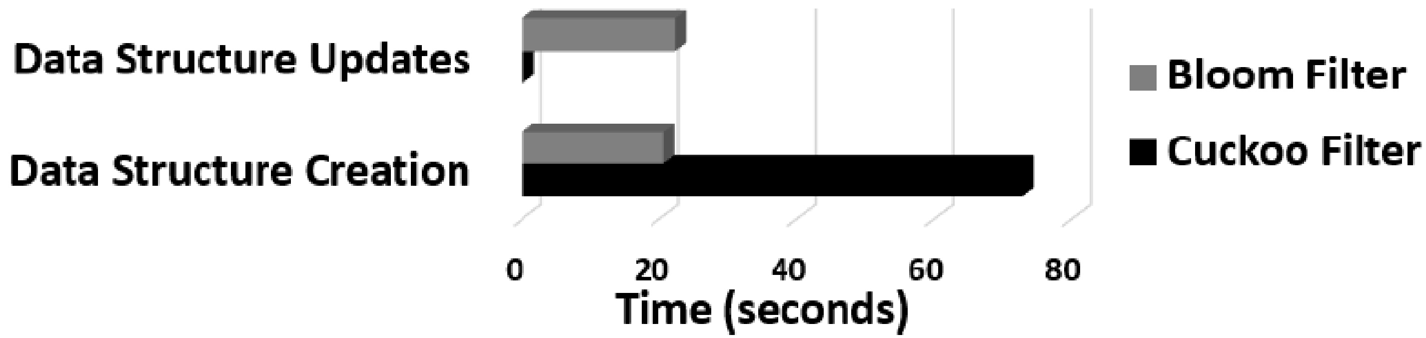
The *Cuckoo Filter* with multiple buckets/*RR* format outperforms the others

Hashed DNS Zones Management

Target: Latency comparison of actions related to managing the *Hashed DNS Zones* using both *Bloom Filters* and *Cuckoo Filters*

Actions:

- Initial creation of the Hashed DNS Zones in memory (***.ru zone***)
- Updating the data structures (1,000 deletions, 1,000 insertions)



- ***Bloom Filters*** **are created faster than** ***Cuckoo Filters*** **due to the element eviction process of** ***Cuckoo Filter*** **insertions (single time action)**
- ***Cuckoo Filters rapidly incorporate changes (Bloom Filters are rebuilt)***

Conclusion & Future Work

Our approach is promising for distributing *Authoritative DNS Server* zone names efficiently, while preserving privacy

Future Work:

- Investigate recently proposed probabilistic data structures, e.g. *Morton Filters*, *Xor Filters* and *Vacuum Filters*
- Employ data plane programming to protect the open channel used for relaying zone exchanges (*XDP*)
- Adapt solution to the mitigation of amplification *NXNSAttacks*
- Develop a Distributed and Federated Learning detection mechanism that will reduce our zone sizes by excluding infrequently requested names

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Open-Sourced Code:

https://github.com/nkostopoulos/dnspriv

Contact Details: **nkostopoulos@netmode.ntua.gr**

THANK YOU!