Digital Signatures for Flows and Multicasts

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Digital Signature

- Examples: RSA, DSA
- Provide authenticity, integrity and non-repudiation
- How to sign and verify?
  - signing key k_s , verification key k_v , message digest $h(m)$
  - $signature = sign(h(m), k_s)$
  - $verify(signature, h(m), k_v)$ = True/False
- Signing & verification operations are slow compared to symmetric key operations

Motivation

- Traditional network applications (circa 1998)
  - message-oriented unicast,
    e.g., email, file transfer, client-server
- Emerging network applications
  - flow-oriented, e.g., audio, video, stock quotes
  - multicast, e.g., teleconference, software distribution
- Problem: How to sign/verify efficiently for high-speed transmissions?
  - real-time generated flows
  - delay-sensitive packet flows

All-or-nothing flows

- The signer generates a message digest of the entire flow (file) and signs the message digest

- But many Internet applications do not create *all-or-nothing* flows
  - a flow is sent as a sequence of packets – also, a subsequence may be usable
  - each packet is used as soon as it is received

Sign-each Approach

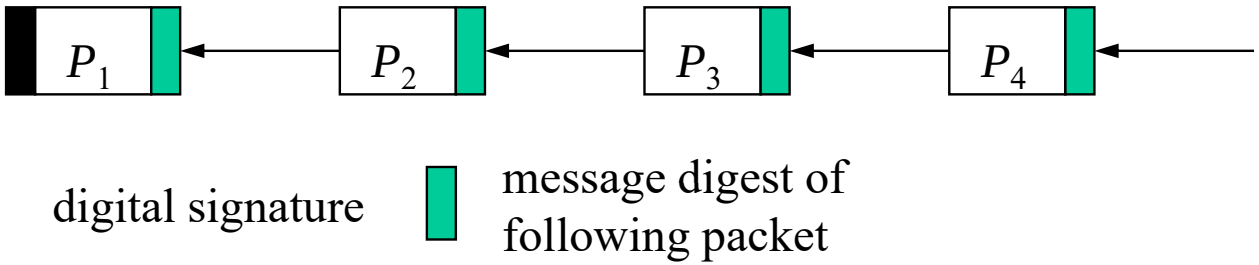
- A flow is a sequence of data packets
- Sign each packet individually
- Inefficient: one signing/verification operation per packet
- Rates on a Pentium-II 300 MHz using 100% processing time (with 512-bit modulus)

Packet size (bytes)	Rate (packets/sec)			
	Signing		Verification	
	RSA	DSA	RSA	DSA
512	78.8	176	2180	128
1024	78.7	175	1960	127

Update: today's processor speed is much higher but Cisco's recommended RSA modulus size is 2048 bits to 4096 bits

Prior work on signing digital streams

- [Gennaro and Rohatgi 1997]
- One signing/verification op for an entire flow—only the first packet is signed
  - Each packet contains authentication info for next
- Verification of each packet depends on previous ones
  - *Reliable delivery* required

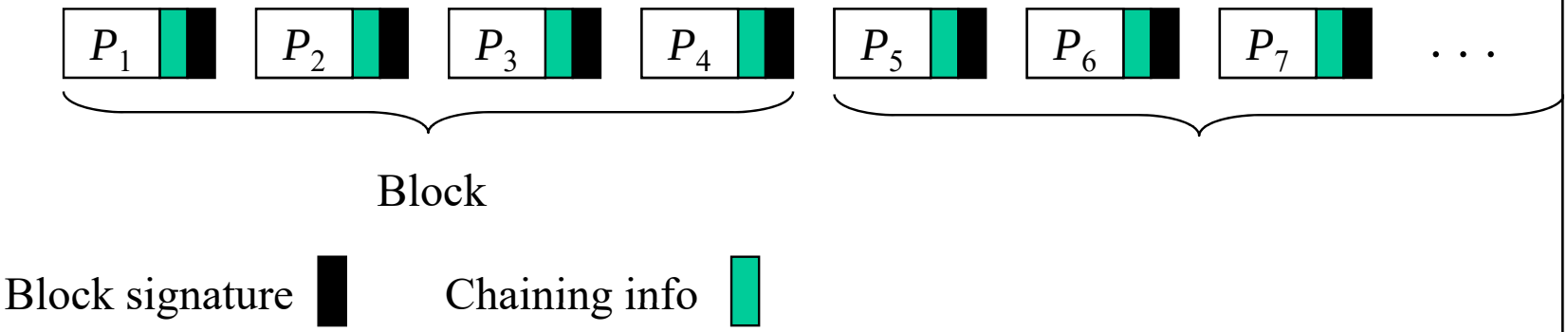


Flow Signing Problem

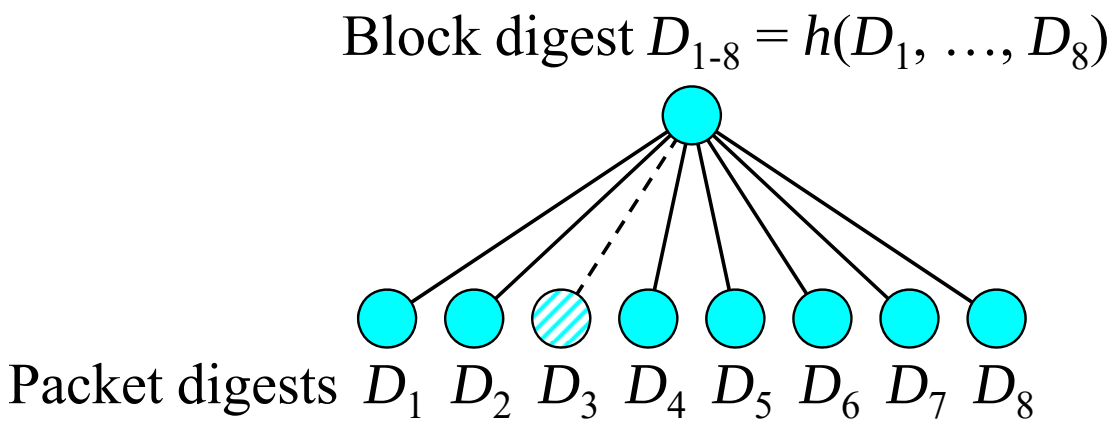
- Each packet may be used as soon as it is received
- Subsequences of a flow are received and used
  - best-effort delivery, e.g., UDP, IP multicast
  - different needs/capabilities, e.g., layered video
- How to efficiently sign flows with each packet being *individually verifiable*?
  - Actually, packets do not have to belong to the same flow to reduce signing cost! E.g. in a multicast

Our Approach: Chaining

- Partition a flow into blocks of packets
  - Sign the digest of each block instead of each packet individually
- Each packet carries its own authentication information to prove it is in the block
  - Authentication info provided by chaining



Star Chaining – Signing



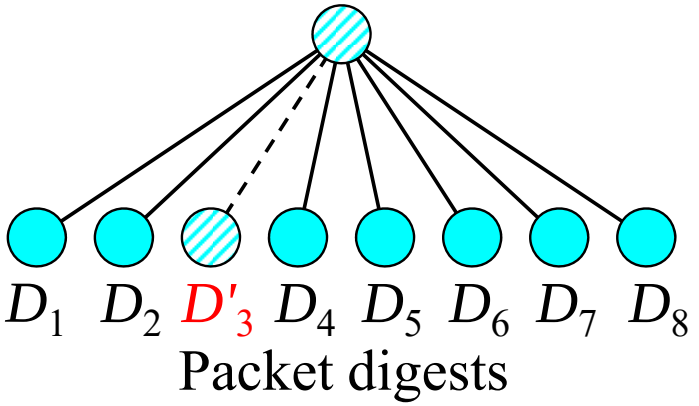
- Block signature = *sign*($D_{1\text{-}8}$)
- Packet signature for packet P_3:

  sign($D_{1\text{-}8}$), D_1, D_2, D_4, …, D_8
- Chaining overhead is *O*(block size)

Star Chaining – Verification

- Verifying first received packet (say P_3)

Block digest $D'_{1\text{-}8} = h(D_1, D_2, D'_3, D_4, \ldots, D_8)$

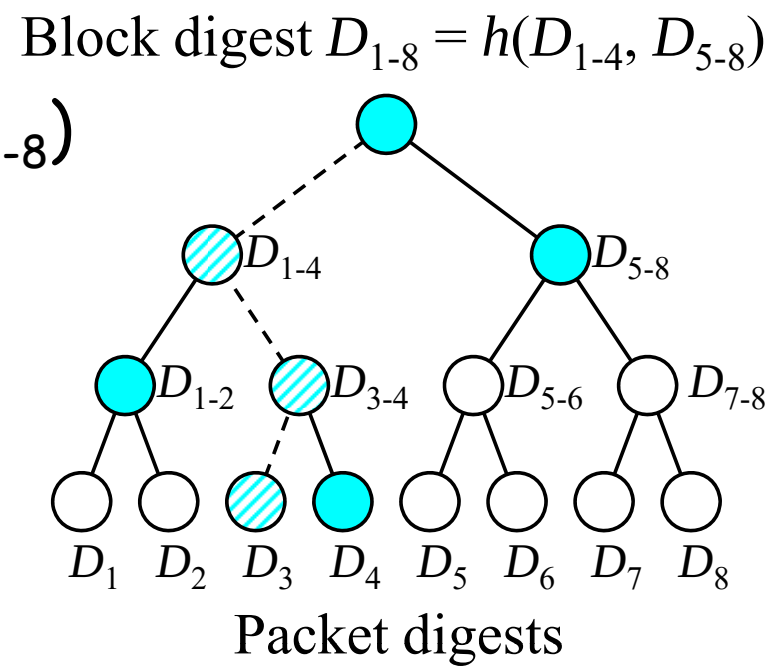


  - *verify*($D'_{1\text{-}8}$, *sign*($D_{1\text{-}8}$))

- Caching of verified nodes
  - no verification op for other packets in the block

Tree Chaining – Signing

- Merkle tree (hash tree) [1989]
- Block signature = $sign(D_{1\text{-}8})$
- Packet signature for packet P_3:
  $sign(D_{1\text{-}8})$, D_4, $D_{1\text{-}2}$, $D_{5\text{-}8}$
- Chaining overhead is $O(log(\text{block size}))$

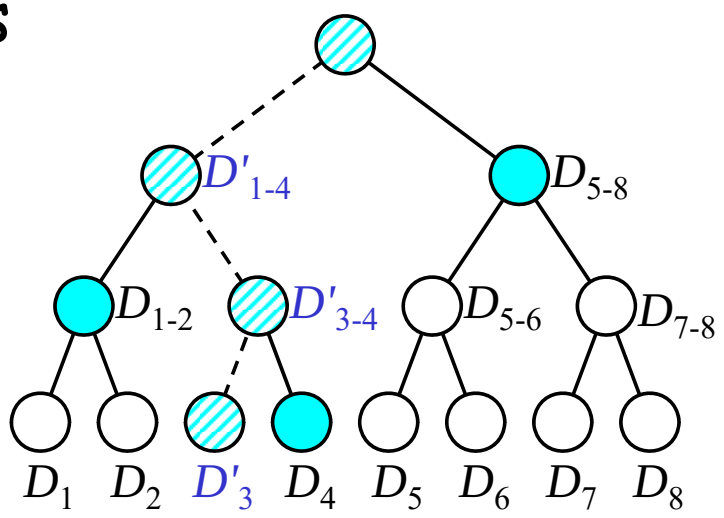


Tree Chaining – Verification

- Verifying first received packet (say P_3)
  - *verify*($D'_{1\text{-}8}$, *sign*($D_{1\text{-}8}$))

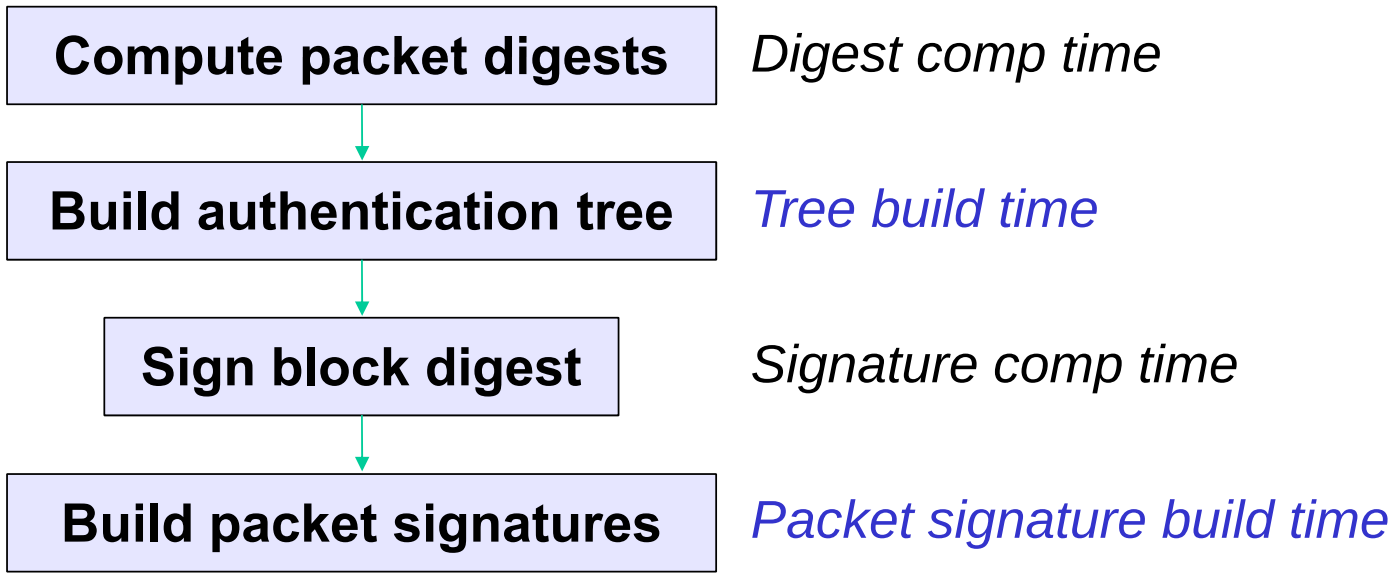
Block digest $D'_{1\text{-}8} = h(D'_{1\text{-}4}, D_{5\text{-}8})$

- Caching of verified nodes
  - no verification op for other packets in the block



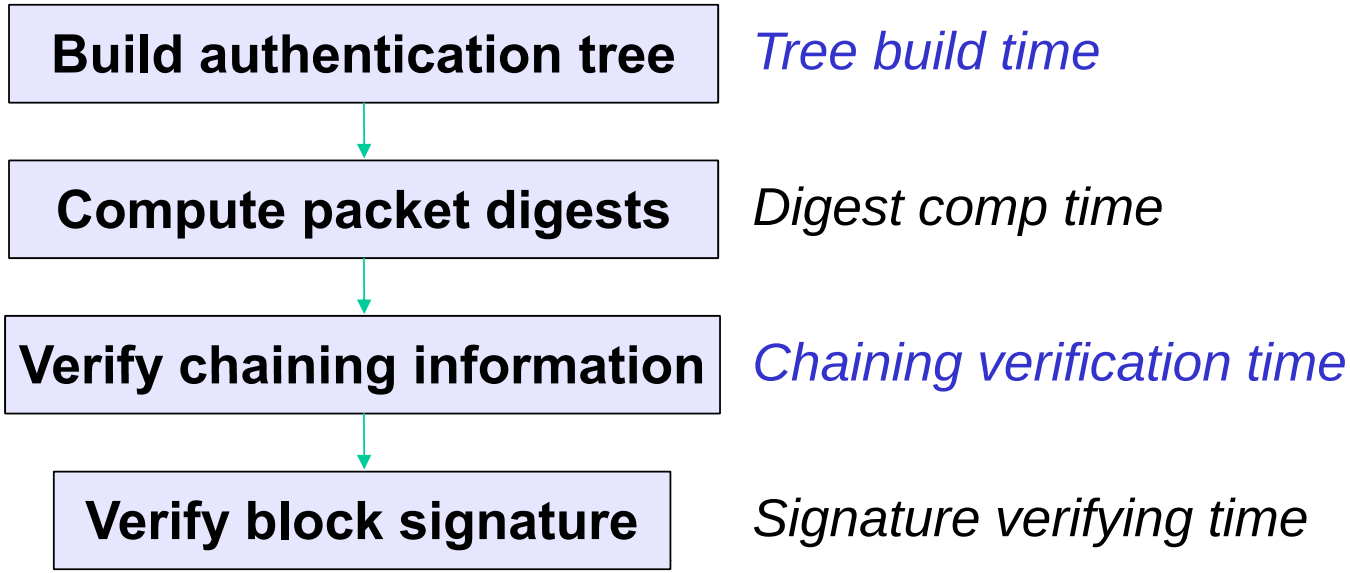
Packet digests

Chaining Technique: Signer Overhead



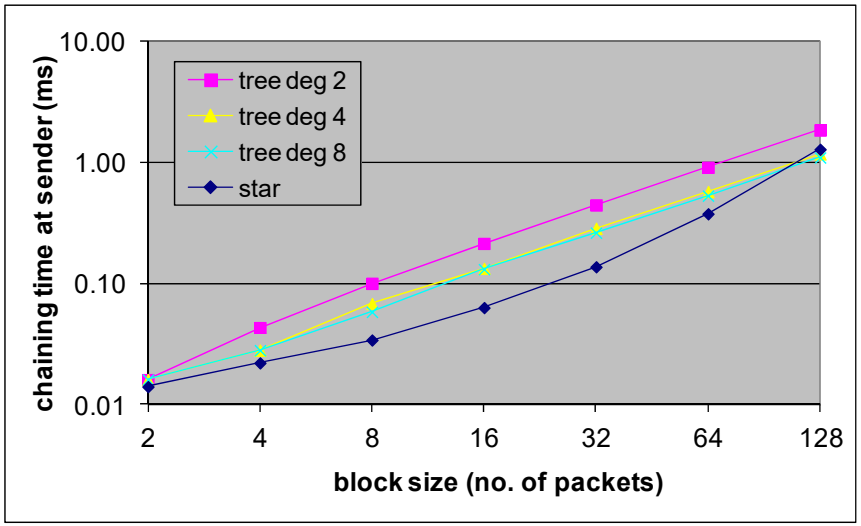
Chaining time = Tree build time + Packet signature build time

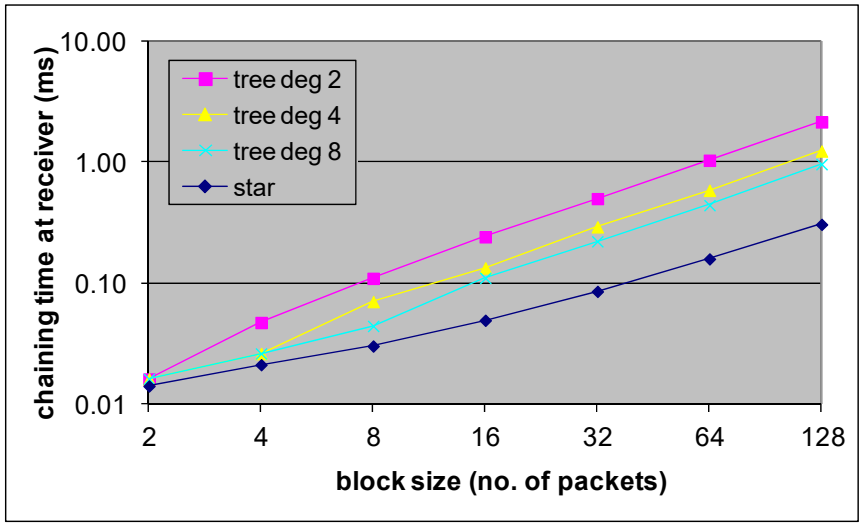
Chaining Technique: Verifier Overhead



Chaining time = Tree build time + Chaining verification time

Chaining Time Overheads



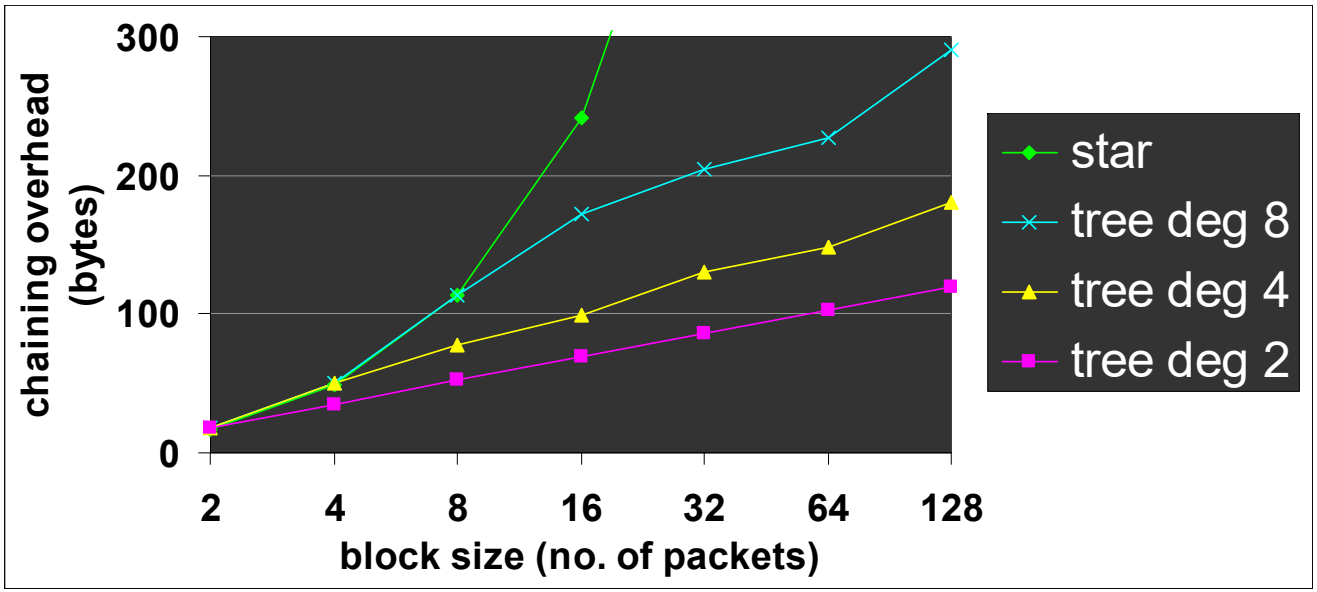


at sender

at receiver

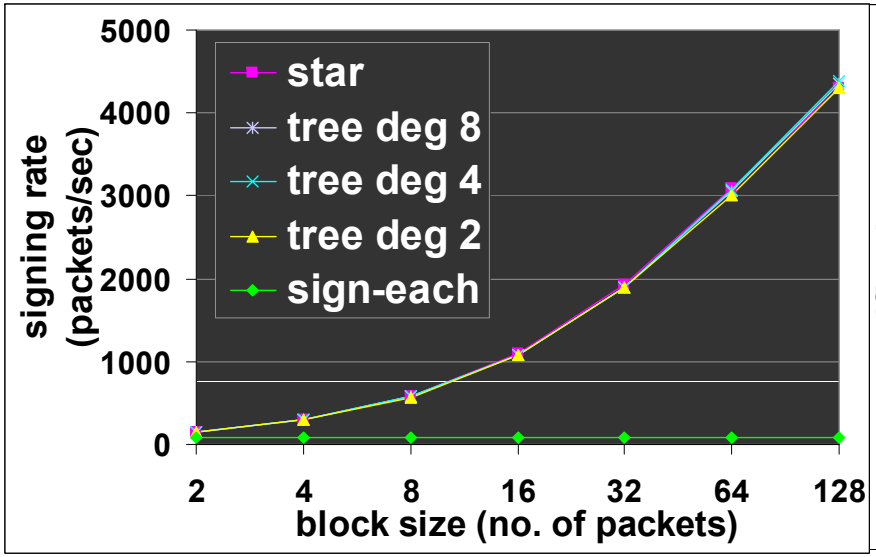
- Overheads increases with block size (both axes in log scale)
- Much smaller than signing/verification times

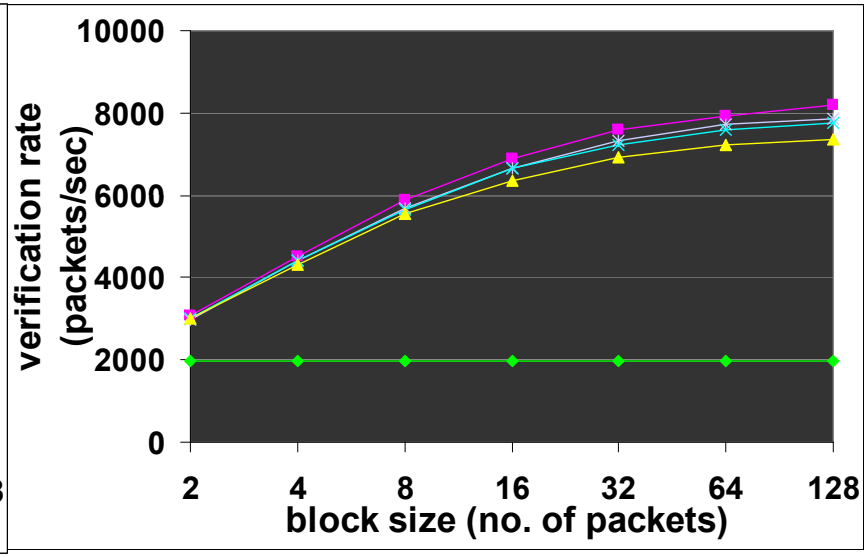
Chaining Overhead Size



- Smallest when tree degree is 2
- Increases linearly with logarithm of block size
- Packet signature = block signature + chaining overhead

Flow Signing/Verification Rates



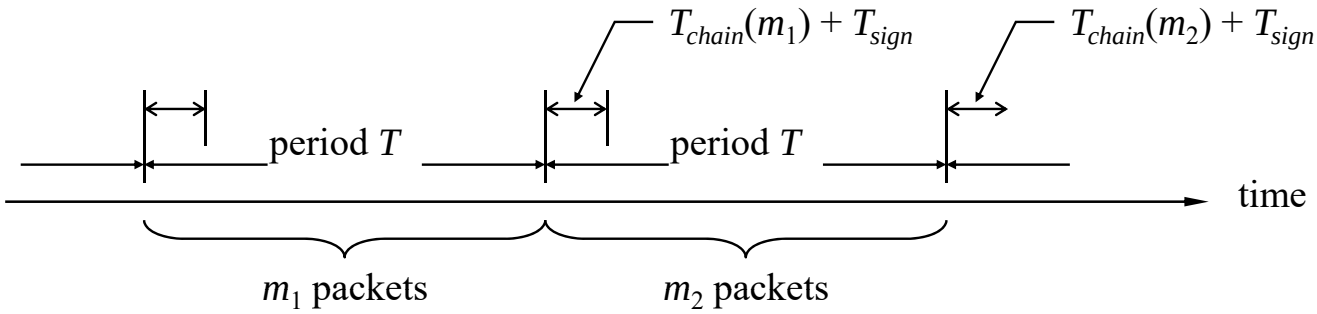


- 1024-byte packets, RSA with 512-bit modulus
- Increases with block size
- Varies only slightly with tree degree
  - we recommend degree 2 tree chaining

Real-time Generated Flows

- Fixed block size for non-real-time generated flows
- Fixed time period T for real-time generated flows
  - Bounded delay signing since for any packet:

    $delay \leq T + T_{chain} + T_{sign}$



  - T should be larger than $T_{chain} + T_{sign}$
  - *delay* cannot be smaller than $2(T_{chain} + T_{sign})$

Selecting a Signature Scheme

- RSA: signing rate not high enough
- DSA: both rates not high and
  verification rate < signing rate
  - In a group, receivers may have widely different resources, e.g., sensors, phones, notebooks, desktops
- We proposed several extensions to FFS
  [Feige, Fiat and Shamir 1986]

FFS Signer

- choose two large primes p and q
- compute modulus $n = pq$
- choose integers $v_1, \ldots, v_k$

  $s_1, \ldots, s_k$

  such that $s_i^2 = v_i^{-1} \bmod n$
- signing key is $\{s_1, \ldots, s_k, n\}$
- verification key is $\{v_1, \ldots, v_k, n\}$

How to Sign Message m

- choose t random integers, $r_1, \ldots, r_t$, between 1 and n
- compute $x_i = r_i^2 \bmod n$, for $i = 1, \ldots, t$
- compute digest $h(m, x_1, \ldots, x_t)$ of message m

  where function $h(\cdot)$ is public knowledge and produces a digest of at least $k \times t$ bits

  let $\{b_{ij}\}$ be the first $k \times t$ bits of the digest
- compute $y_i = r_i \times (s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}}) \bmod n$

  for $i = 1, \ldots, t$
- signature of m consists of

  $\{y_i\}$ and $\{b_{ij}\}$ for $i = 1, \ldots, t$ and $j = 1, \ldots, k$

How to Verify Signature of Message m

- signature of m

  $\{y_i\}$ and $\{b_{ij}\}$ for $i = 1, \ldots, t$ and $j = 1, \ldots, k$

- compute $z_i = y_i^2 \times (v_1^{b_{i1}} \times \ldots \times v_k^{b_{ik}}) \bmod n$

  for $i = 1, \ldots, t$

  it can be shown that z_i is equal to x_i at the signer

- signature is valid if and only if the first

  $k \times t$ bits of $h(m, z_1, \ldots, z_t)$ are equal to the $\{b_{ij}\}$ received in signature

FFS(k,t)

- security level increases with
  - size of modulus *n* (or size of primes *p* and *q*)
  - value of product *kt*

- key size is (k+1) x |n|
  assuming |n| = $|v_i|$ or $|s_i|$ in bits

- signature size is *t* x | *n* | + *k* x *t* bits
  minimized for *t*=1

FFS key and signature sizes

FFS Signing/Verification Key and Signature Sizes (Bytes) With 512-Bit Modulus

	$t = 1$		$t = 2$		$t = 4$	
	key	sig	key	sig	key	sig
$kt = 64$	4160	72	2112	136	1088	264
$kt = 128$	8256	80	4160	144	2112	272

For a fixed *kt* product, signature size is minimized for *t* =1, but key size is maximized

eFFS Signature Scheme

- Several extensions to FFS [Feige, Fiat and Shamir 1986]
  - Faster signing
    - Chinese remainder theorem (*crt*)
    - Precomputation (*4-bit, 8-bit*)
  - Faster verification
    - Small verification key (*sv-key*) [Micali & Shamir 1990]
  - Adjustable and incremental verification
    - multilevel signature
    - lower security level with less processor time at receiver
    - security level can be increased later by more processor time

eFFS extension (1)

- Chinese remainder theorem

  instead of $y_i = r_i \times (s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}}) \bmod n$

  signer computes

  $a_i = r_i \times (s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}}) \bmod p$

  $b_i = r_i \times (s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}}) \bmod q$

  $y_i = ((a_i - b_i) \times q \times q_p^{-1} + b_i) \bmod n$

  where q_p^{-1} denotes $q^{-1} \bmod p$,

  - multiplications in mod p and mod q faster than in mod n

- Only signer knows p and q

eFFS extension (2)

- small verification key [Micali & Shamir]:

  use first k prime numbers that satisfy

  $$s^2 = p^{-1} \bmod n$$

  where p is prime and s is an integer

- faster verifying time and smaller key size

eFFS extension (3)

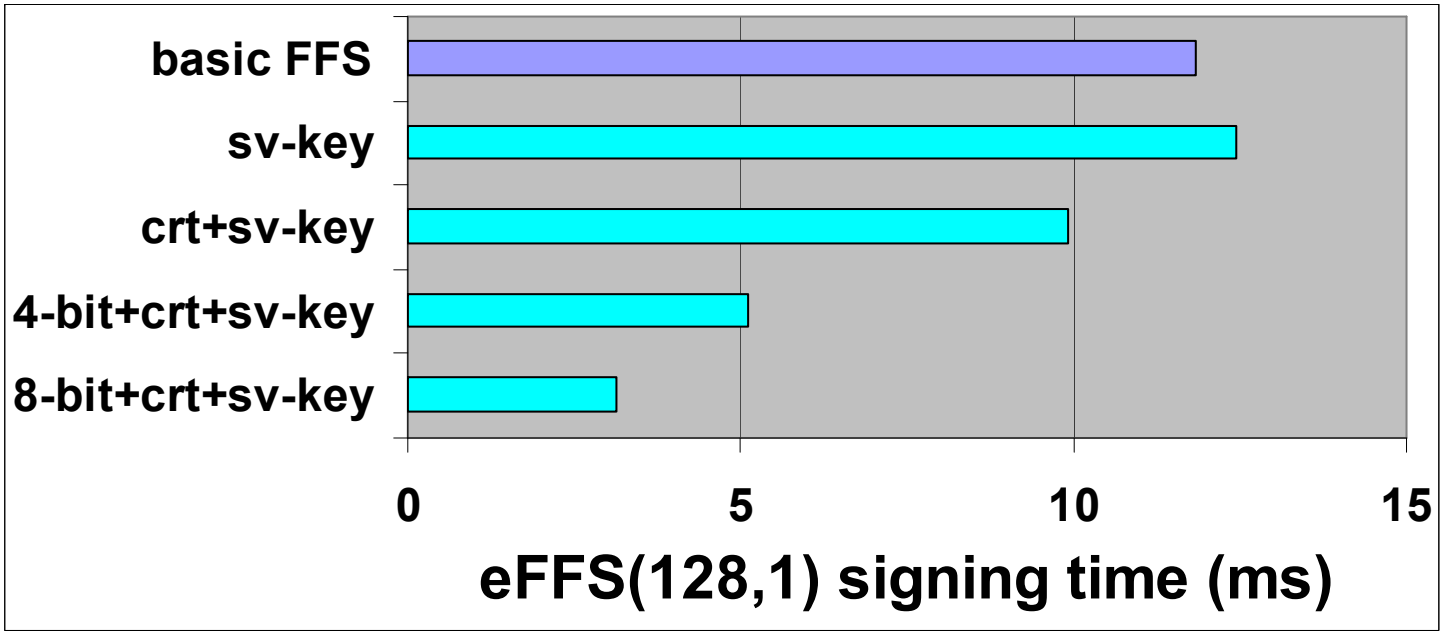
- To compute $y_i = r_i \times (s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}}) \bmod n$ for $i = 1, \ldots, t$

- precomputation of $(s_1^{b_{i1}} \times \ldots \times s_k^{b_{ik}})$

  additional memory of 31 KB and 261 KB required for 4-bit and 8-bit precomp respectively

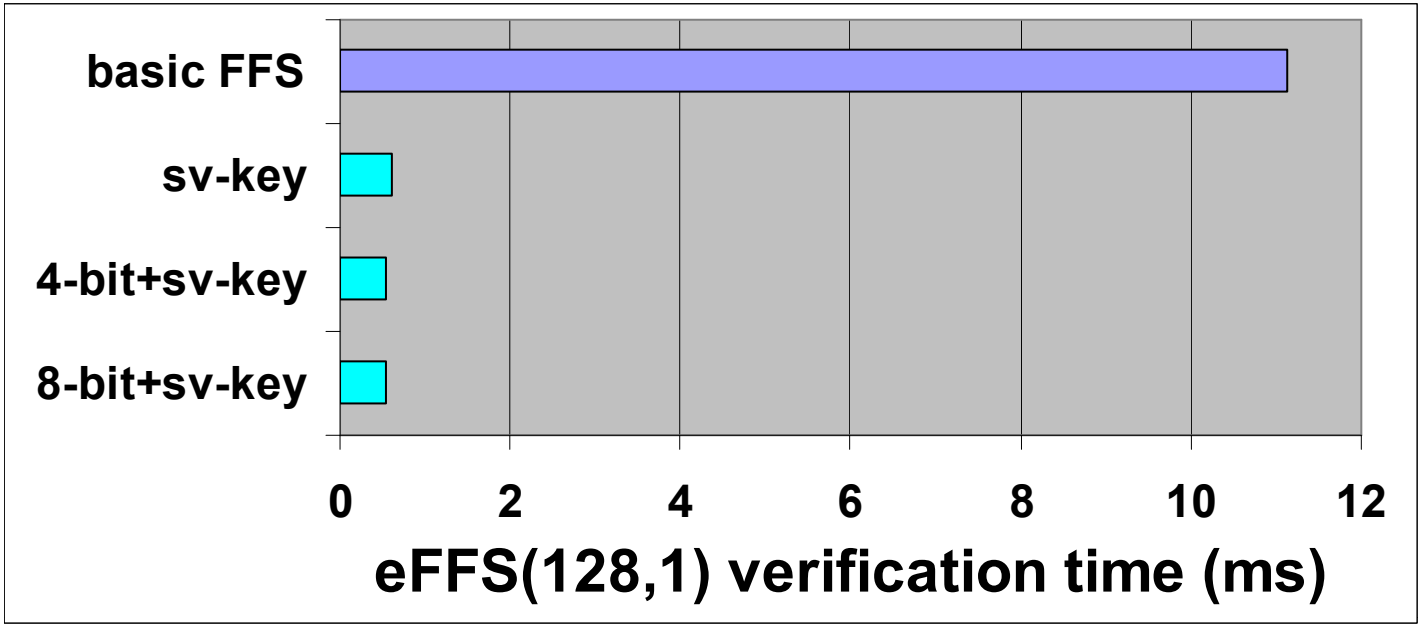
  - only minor improvement at verifier when used with small v-keys

eFFS – Signing



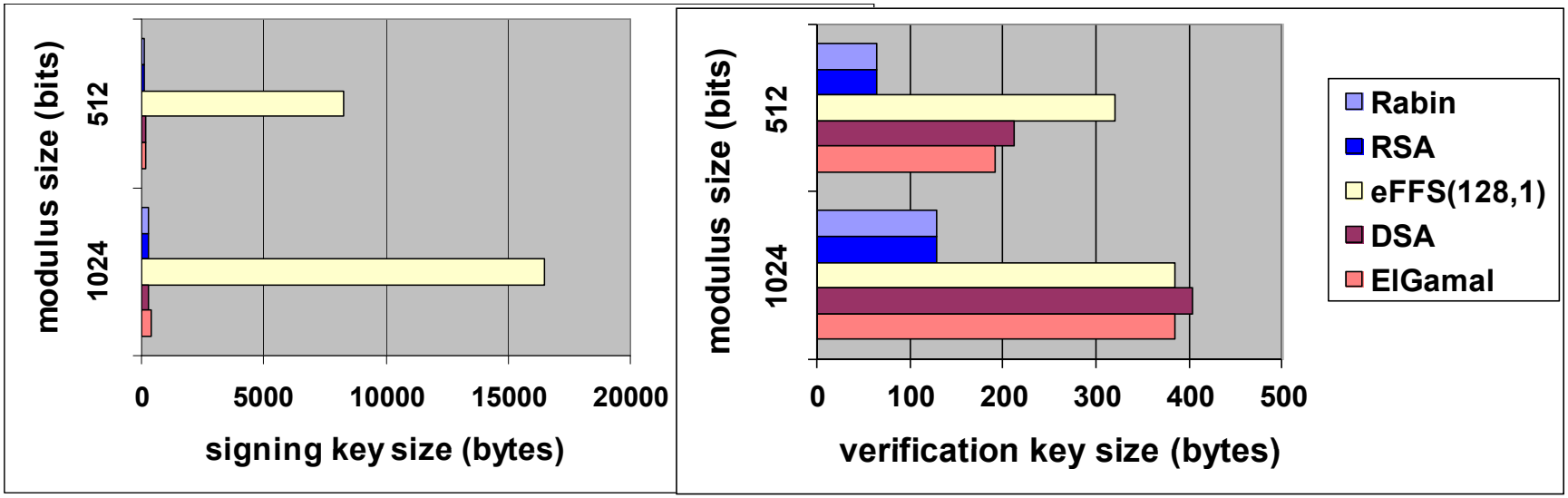
- sv-key does not reduce signing time
- crt reduces signing time by 10-20%
- 8-bit + crt reduces signing time by 60-70%

eFFS – Verification



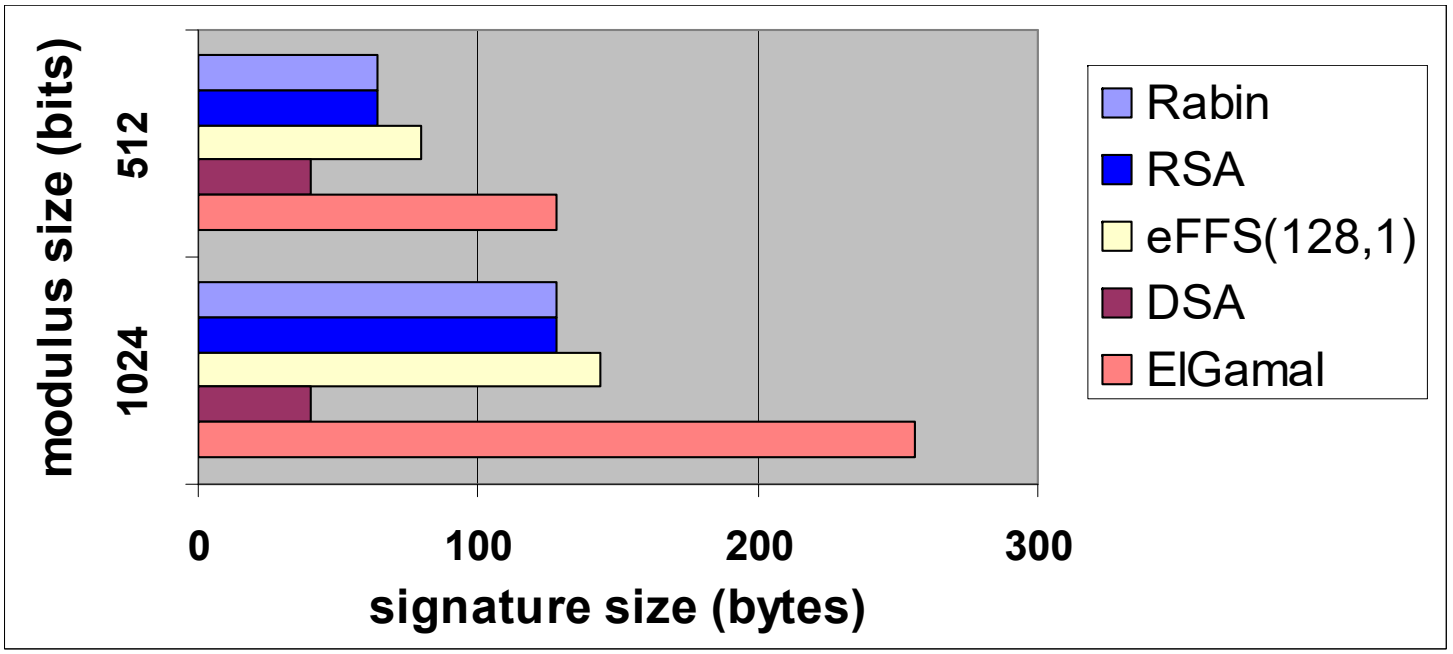
- sv-key reduces verification time by 90%
- 4-bit or 8-bit slightly reduces verification time

eFFS Key Size



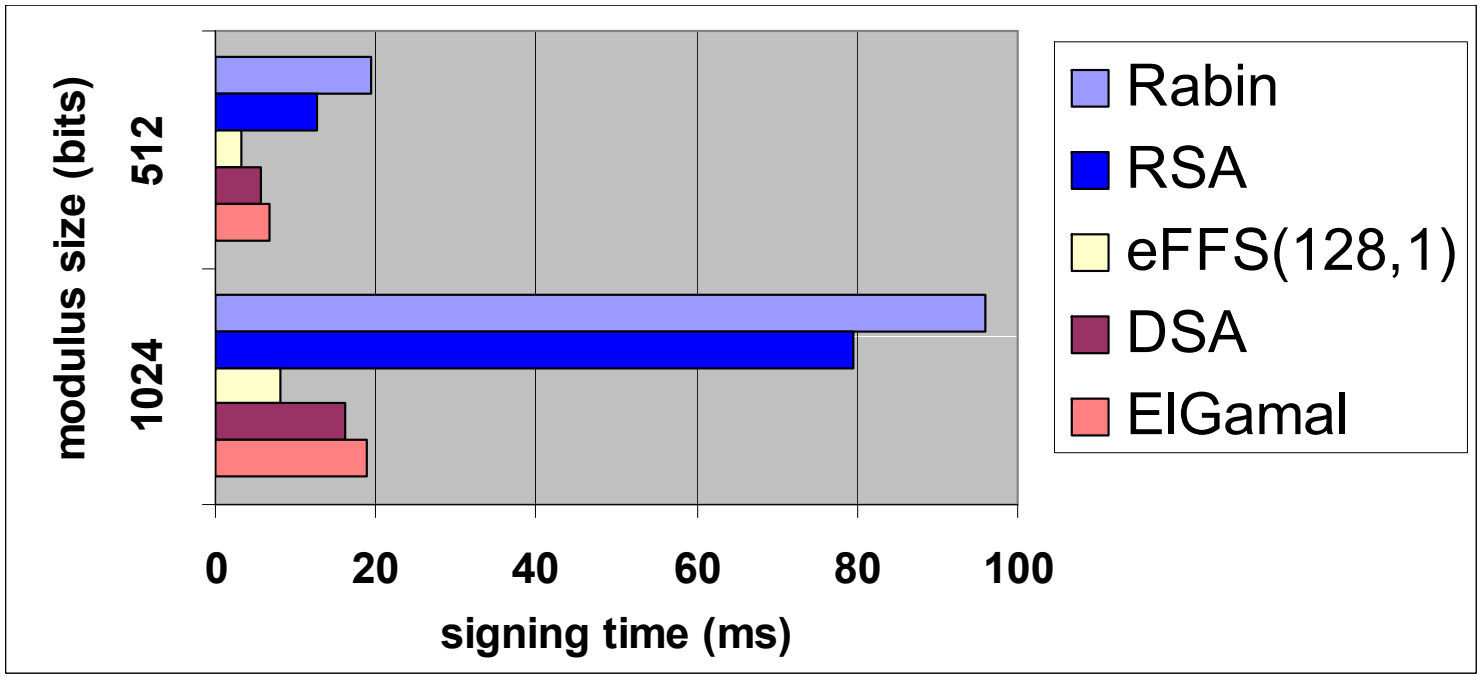
- Large signing key 8000-17000 bytes
  - private to signer
- Verification key 300-400 bytes

eFFS Signature Size



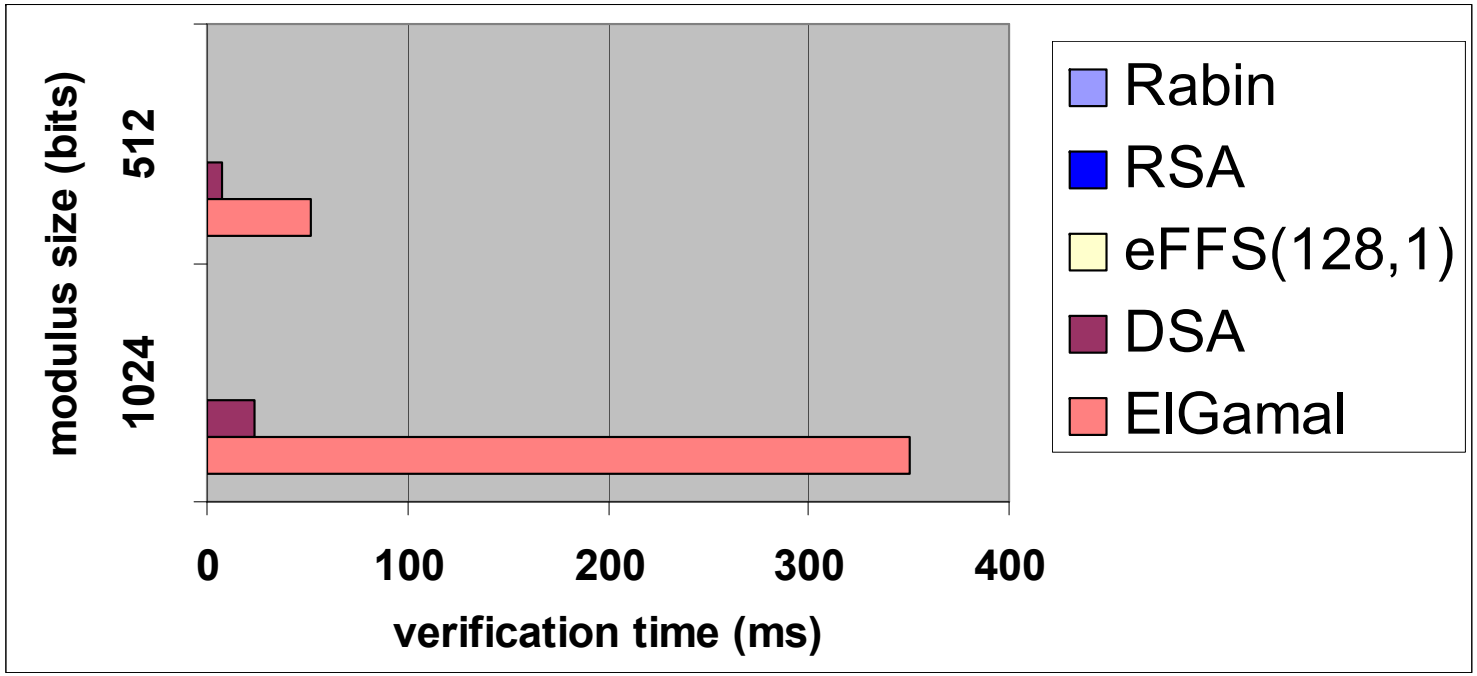
- Signature size comparable to RSA and Rabin

Signing Time Comparison



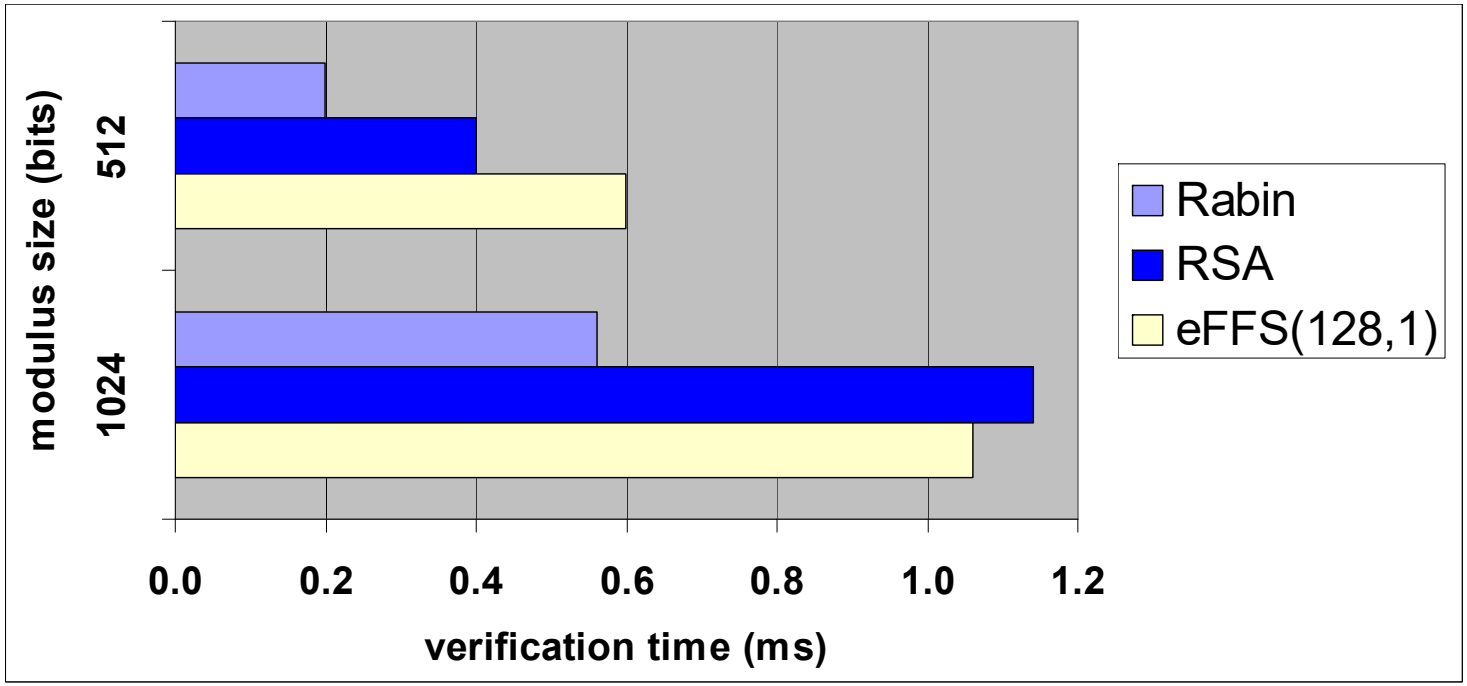
- 8-bit + crt + sv-key extensions
- **eFFS has the *smallest signing time***

Verification Time Comparison



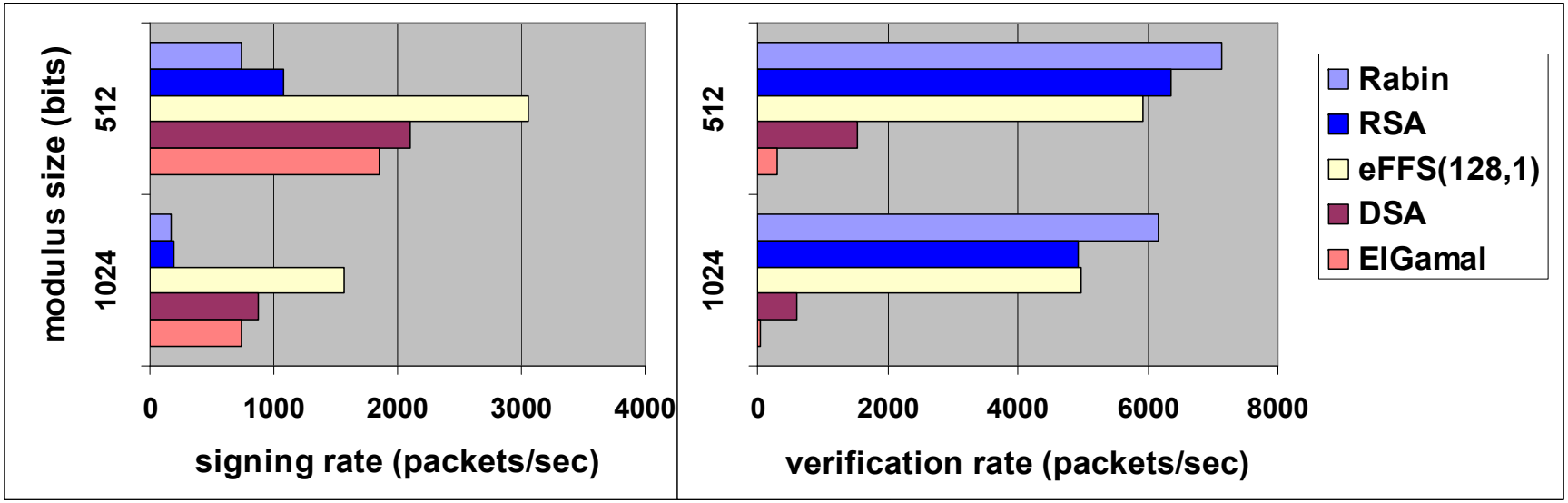
- DSA and ElGamal verification times very large
- Rabin, RSA and eFFS too small to see

Verification Time Comparison



- eFFS verification time comparable to RSA (Rabin most efficient verification)

Flow Signing/Verification Rates



- 1024-byte packets, block size 16, degree two tree chaining
- eFFS has highest signing rate
- eFFS verification rate comparable to RSA

eFFS Adjustable and Incremental Verification

- Security level of eFFS(k,t) depends on modulus size and product kt
  - same kt and modulus size ~ same security level

- Adjustable and incremental verification
  - using $t > 1$ with additional info in signature
  - *up to t steps*
  - adjustable and incremental:
    receiver verifies steps one by one

eFFS Adjustable and Incremental Verification (cont.)

- t-level signature includes $\{x_i\}$ for $i = 2, \ldots, t$

  note that $\{x_i\}$ can be computed from original signature together with verification key

- verify a t-level signature at security level $l \leq t$,
  (1) compute $z_i = y_i^2 \times (v_1^{b_{i1}} \times \ldots \times v_k^{b_{ik}}) \bmod n$ for $i = 1, \ldots, l$,
  (2) verify that the first $k \times t$ bits of $h(m, z_1, x_2, \ldots, x_t)$ are equal to the $\{b_{ij}\}$ received

  and $z_2, \ldots, z_l$ are equal to $x_2, \ldots, x_l$

eFFS Adjustable and Incremental Verification (cont.)

- increase security level from l_1 to l_2,

  (1) compute $z_i = y_i^2 \times (v_1^{b_{i1}} \times \ldots \times v_k^{b_{ik}}) \bmod n$ for $i = l_1 + 1, \ldots, l_2$,

  (2) verify that $z_{l_1+1}, \ldots, z_{l_2}$ are equal to $x_{l_1+1}, \ldots, x_{l_2}$

Incremental signing times

eFFS t-Level Signature Signing Times (Milliseconds)

	kt product		
	$kt = 32$	$kt = 64$	$kt = 128$
1-level signature	1.47	2.02	3.14
2-level signature		2.87	3.98
4-level signature			5.67

2-level signature takes less time to sign than two 1-level signatures

Incremental verification times

eFFS Incremental Verification Times (Milliseconds) for $kt = 128$. (a) 2-Level Signature. (b) 4-Level Signature.

To	level 1	level 2
From level 0	0.42	0.81
From level 1		0.40

(a)

To	level 1	level 2	level 3	level 4
From level 0	0.34	0.63	0.93	1.22
From level 1		0.30	0.60	0.89
From level 2			0.30	0.60
From level 3				0.31

(b)

Conclusions

- Flow signing/verification procedures
  - much more efficient than sign-each
  - small communication overhead
  - can be used by a sender that signs a large number of packets to different receivers
    - there is no requirement that the packets belong to a flow but if they do, verification is also more efficient; else, each receiver has to do a bit more work

- eFFS digital signature scheme
  - most efficient signing compared to RSA, Rabin, DSA, and ElGamal
  - highly efficient verification and comparable to RSA (only Rabin is more efficient)
  - adjustable and incremental verification

The End