# GCM-SIV:
# Full Nonce Misuse-Resistant Authenticated Encryption at Under One Cycle per Byte

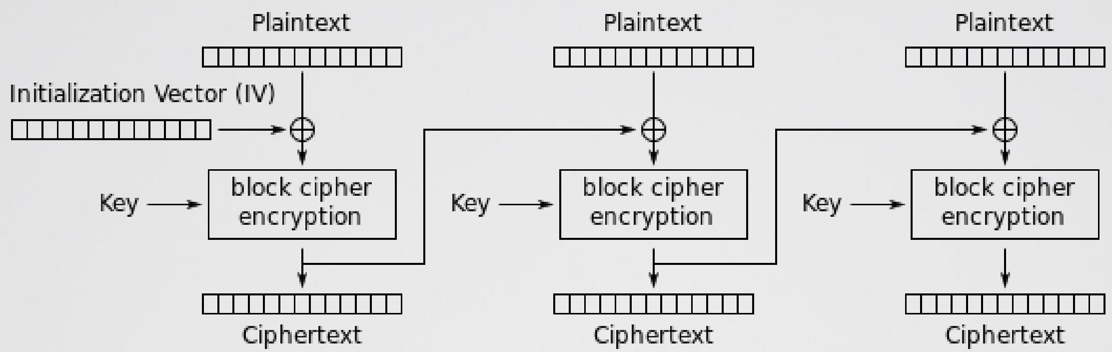
Shay Gueron
Haifa Univ. and Intel

Yehuda Lindell
Bar-Ilan University

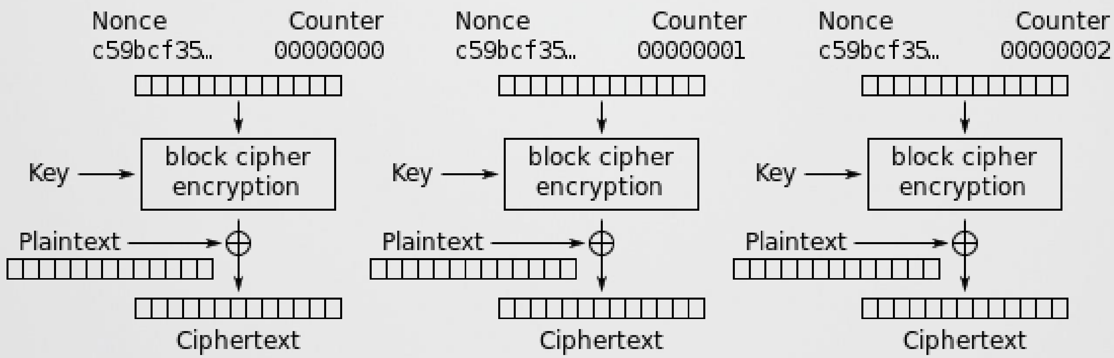
Center for Research in Applied Cryptography and Cyber Security

Appeared at ACM CCS 2015

# How to Encrypt with a Block Cipher




Cipher Block Chaining (CBC) mode encryption



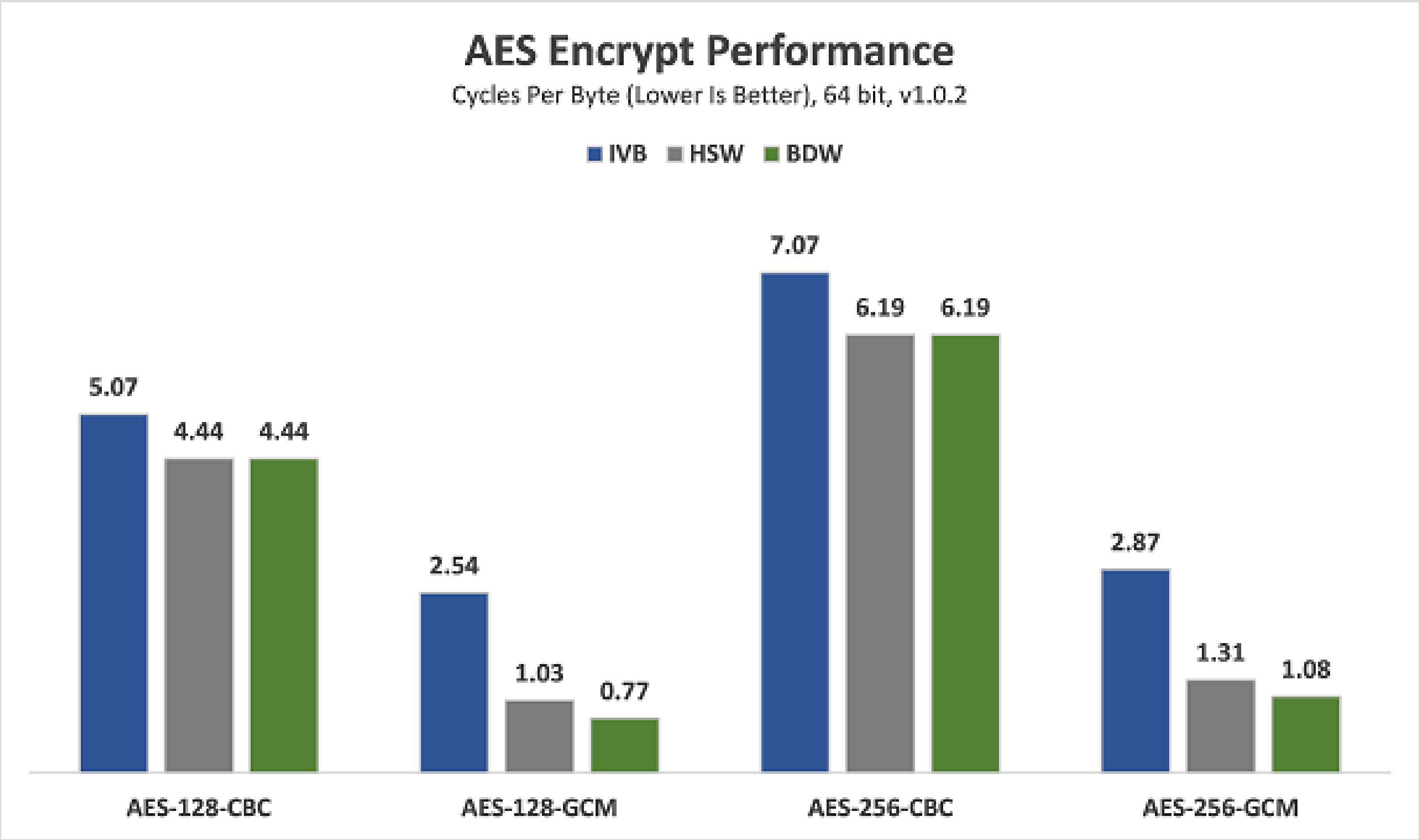

Counter (CTR) mode encryption

# CBC vs CTR

- **Efficiency:**
  - CBC – encryption is strictly **sequential**
  - CTR – encryption can be parallelized

- **Does this matter?**
  - The Intel AES-NI instruction is fully pipelineable
  - AES-CTR encryption with AES-NI is 7 times faster!

# CBC vs CTR

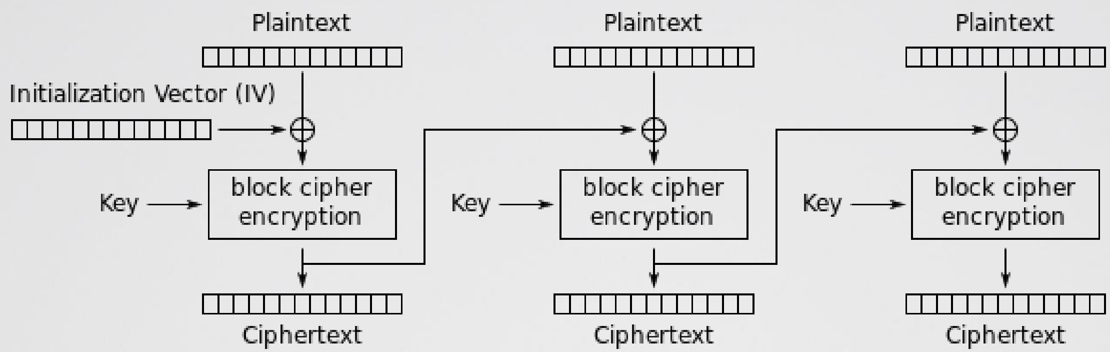


AES Encrypt Performance
Cycles Per Byte (Lower Is Better), 64 bit, v1.0.2
IVB
HSW
BDW
5.07
4.44
4.44
2.54
1.03
0.77
7.07
6.19
6.19
2.87
1.31
1.08
AES-128-CBC
AES-128-GCM
AES-256-CBC
AES-256-GCM

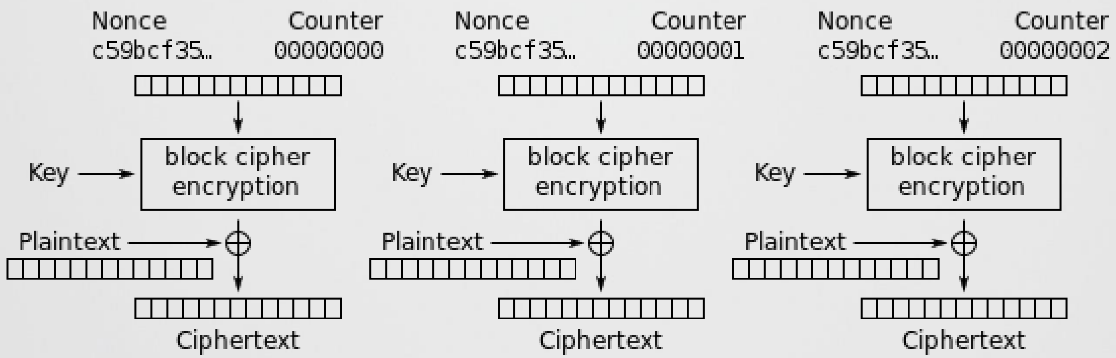
# CBC vs CTR – Security

- **Security bounds**
  - CTR has better security bounds – the counter is a nonce and security is preserved as long as it doesn't repeat
  - CBC breaks at the birthday bound since "random" values are input to the block cipher
- ~~**Integrity**~~
  - ~~CBC is harder to tamper with~~
- **IV/nonce reuse**
  - CBC – reveals common prefix
  - **CTR – completely broken**

# IV/Nonce Reuse




Cipher Block Chaining (CBC) mode encryption




Counter (CTR) mode encryption

# Why Should an IV Repeat?

- **Randomness is much harder than it should be**
  - Intel has RDRAND and RDSEED on all new chips
- **Not used inside Linux /dev/random**

## “We cannot trust” Intel and Via’s chip-based crypto, FreeBSD developers say

Following NSA leaks from Snowden, engineers lose faith in hardware randomness.

by **Dan Goodin** - Dec 10, 2013 3:00pm IST

Share Tweet 143

*This post was updated on December 16 to make clear that for most of FreeBSD's history, it wasn't possible to use RDRAND and Padlock as the sole source of random numbers fed to the /dev/random engine.*

# Bad Randomness

- **In 2008, a bug in Debian Linux was found**
  - In 2006, code that was crucial for RNG reseeding was commented out

```
MD_Update(&m,buf,j);
[ .. ]
MD_Update(&m,buf,j); /* purify complains */
```

# Bad Randomness

- **PlayStation 3**
  - In 2010, the ECDSA private key used by Sony to sign software for PlayStation 3 was recovered because Sony failed to generate a new random nonce for each signature

# RSA Keys – Lenstra et al. 2012

- **Collected 6.4 million RSA keys from the web**
  - 71,052 occurred more than once
    - Different owners can decrypt each other's traffic
    - Some of the moduli repeated thousands of times (no entropy)
  - 12,934 had a common factor
    - Computed $GCD(N, N')$ where $N = pq$ and $N' = p'q$
    - Factor both moduli
- **We use this for entropy estimation**

# Entropy Estimation via RSA Keys

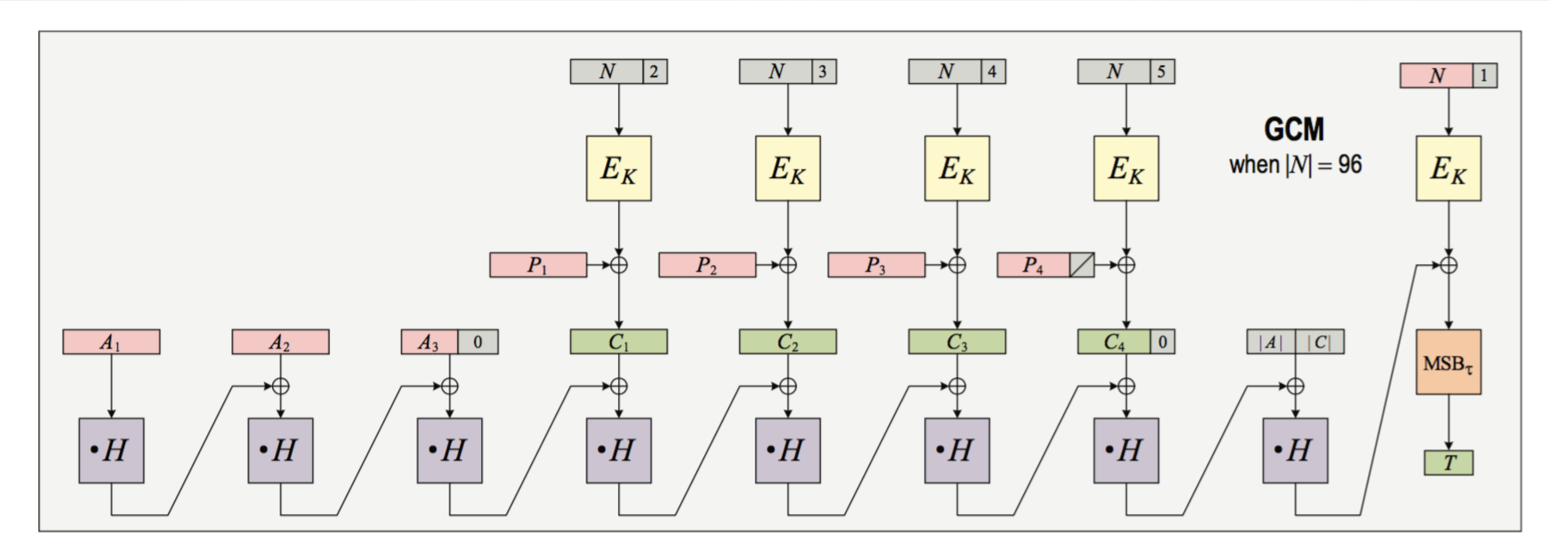
- The expected number of collisions in q samples from a domain of size N is $\binom{q}{2}/_{N} \approx q^2/_{2N}$
- We have $q = 12,800,000$ (number of primes is double)
- We have number of collisions = 12,934
- So, $\frac{12{,}800{,}000^2}{2N} = 12,934$ giving $N \approx 2^{32.56}$
- Conclusion: an "average" of 33 bits of entropy

# Bad Randomness

- Given that randomness can repeat and does repeat, what should we do?
- CBC still reveals common prefixes, but is better than CTR…
- Can we do better? Efficiently?

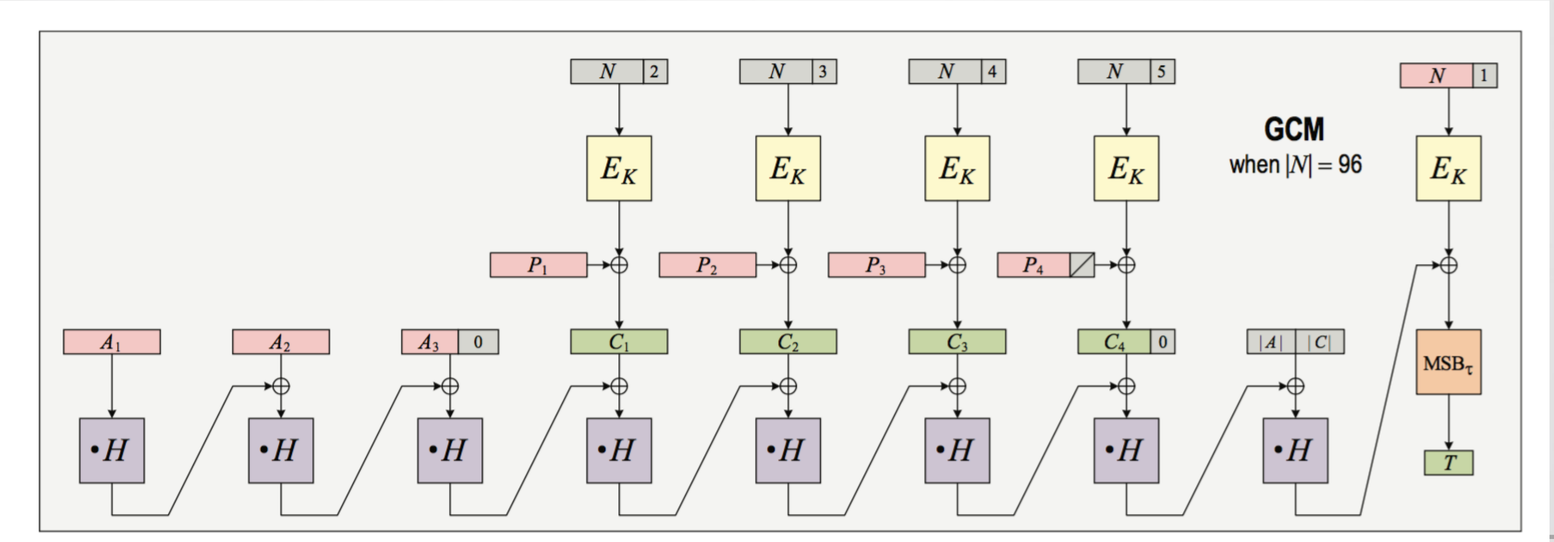
# What About Authenticated Encryption?

- **CCM:**
  - CBC-MAC followed by CTR encryption: **slow due to CBC-MAC** and **vulnerable due to CTR encryption**
- **GCM:**



# What About Authenticated Encryption?

- **GCM – if the nonce repeats, then:**
  - **As with CTR plaintexts can be recovered**
  - Much more seriously – **H can be recovered**
- **This means that integrity is lost forever!**



# Preliminaries: IV vs Nonce Encryption

- **IV (initial vector) encryption:**
  - IV must be randomly chosen
- **Nonce-based encryption:**
  - Only require that nonce is unique

- **CBC encryption:** need random IV; nonce not good enough
- **CTR encryption:** suffices to have a unique nonce
  - In AES-CTR, use a nonce of length 96 bits and counter of length 32 bits

# Nonce Misuse Resistance [Rogaway-Shrimpton]

- Denote nonce by N
- **Security property**
  - If N is same and message is same – the result is the same ciphertext
    - This is inherent
  - Otherwise – full security (authenticated encryption):
    - Even if N is the same and the message is not
    - Even if N is different and the message the same
- **This cannot be achieved for online encryption**
  - If two long messages differ only in the last bit, when same N is used, must have same prefix in online

# Abstract SIV Encryption [Rogaway-Shrimpton]

- **Input:** message $M$ and nonce $N$
- **Step 1:**
  - Apply a PRF $F$ with key $K1$ to $(N, M)$; denote result by $T$
- **Step 2:**
  - Encrypt $M$ with key $K2$ using nonce $T$; denote result by $C$
- **Output** $(N, M, T)$

- **Decryption:** $M \leftarrow Dec_{K2}(C)$ with nonce $T$; check $T = F_{K1}(N, M)$

# SIV Encryption Security

- **Encryption:**

$$T = F_{K1}(N, M);\ C \leftarrow Enc_{K2}(M) \text{ with nonce } T$$

- **Security**
  - If nonce $N$ is different, then by PRF the value $T$ is pseudorandom
  - If nonce $N$ is the same but $M$ is different, then by PRF the value $T$ is pseudorandom
  - The value $T$ also serves as a valid MAC and so have authenticated encryption

# Efficient Instantiations

- **Option 1 – apply a PRF based on AES**
  - What PRFs do we have? CBC-MAC
  - Very expensive

- **Option 2 – construct a more efficient PRF using simpler primitives**
  - Let $H$ be an $\epsilon$-XOR universal hash function
$$\forall x, y, z : \Pr[H_{K1}(x) \oplus H_{K1}(y) = z] \leq \epsilon(n)$$

- **Claim:** $F_{K1,K2}(N, M) = F_{K2}(H_{K1}(M) \oplus N)$ **is a PRF**

# Universal-Hash Based PRF

- **The construction:** $F_{K1,K2}(N, M) = F_{K2}(H_{K1}(M) \oplus N)$
- **Proof idea:**
  - By the PRF property of $F$, can distinguish only if it queries $(N, M), (N', M')$ where $H_{K1}(M) \oplus N = H_{K1}(M') \oplus N'$
  - Equivalently: if $H_{K1}(M) \oplus H_{K1}(M') = N \oplus N'$
  - By the $\epsilon$-XOR property, this happens with probability only $\epsilon$ for each pair
  - Therefore, secure PRF for negligible $\epsilon$

# The GCM-SIV Instantiation

- **The GHASH function H in GCM is an $\epsilon$-XOR universal hash function (for negligible $\epsilon$)** [McGrew-Viega]
- **The PRF used is AES (only need a single block)**
- **Encryption is AES-CTR**

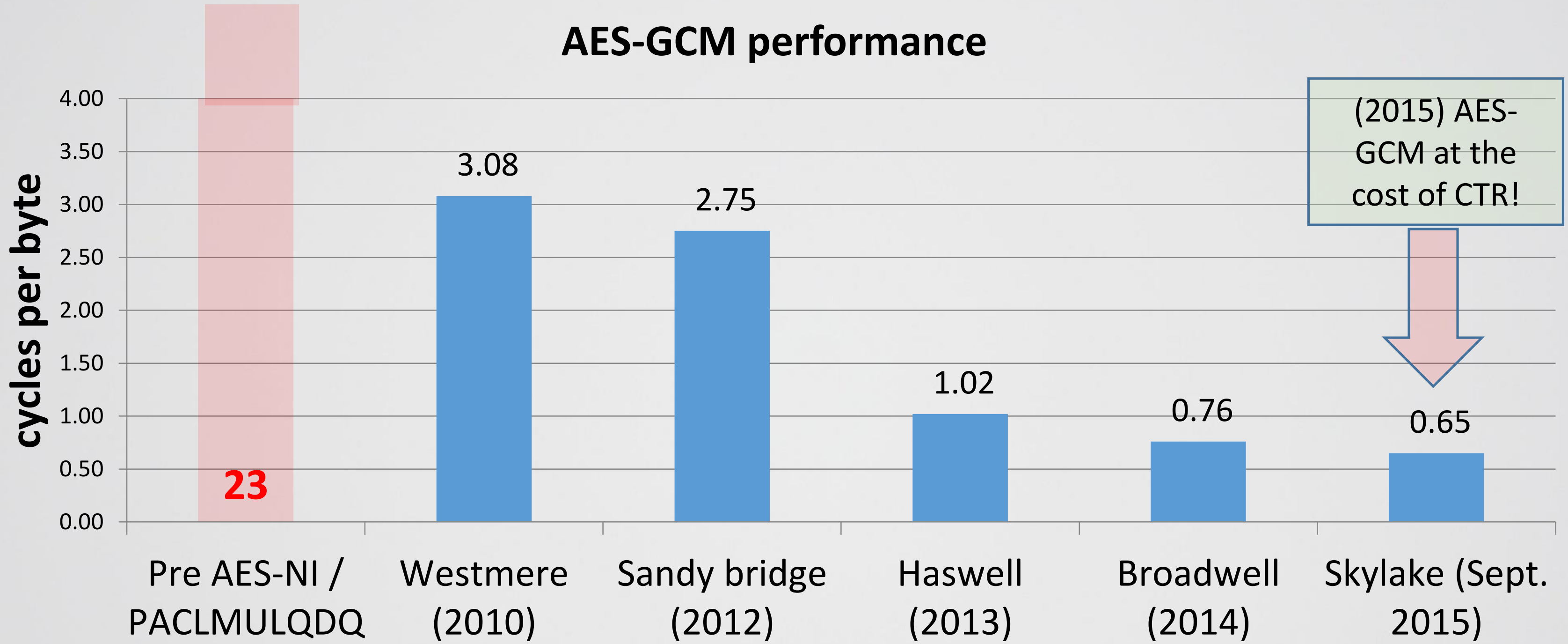
- **Versions:**
  - Three different keys (for GHASH, PRF, CTR-ENC)
  - Two keys: use same key for PRF and CTR-ENC
  - One key: derive the two keys using AES itself

# The GCM-SIV Instantiation

- **A very important property: all the elements here are identical to the existing AES-GCM**
  - We only change the order of operations

- **Why is this important?**
  - Efficiency
  - Deployment ease (use existing code bases)

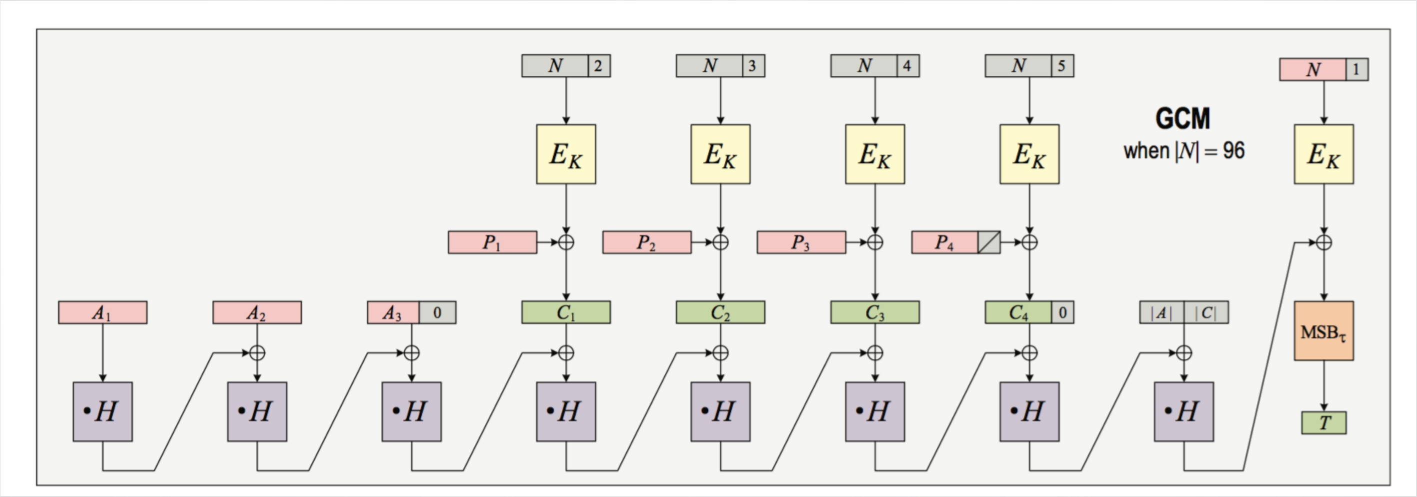
# AES-GCM Across Intel CPU Generations




**Use AES-NI for CTR and PCLMULQDQ for GHASH**

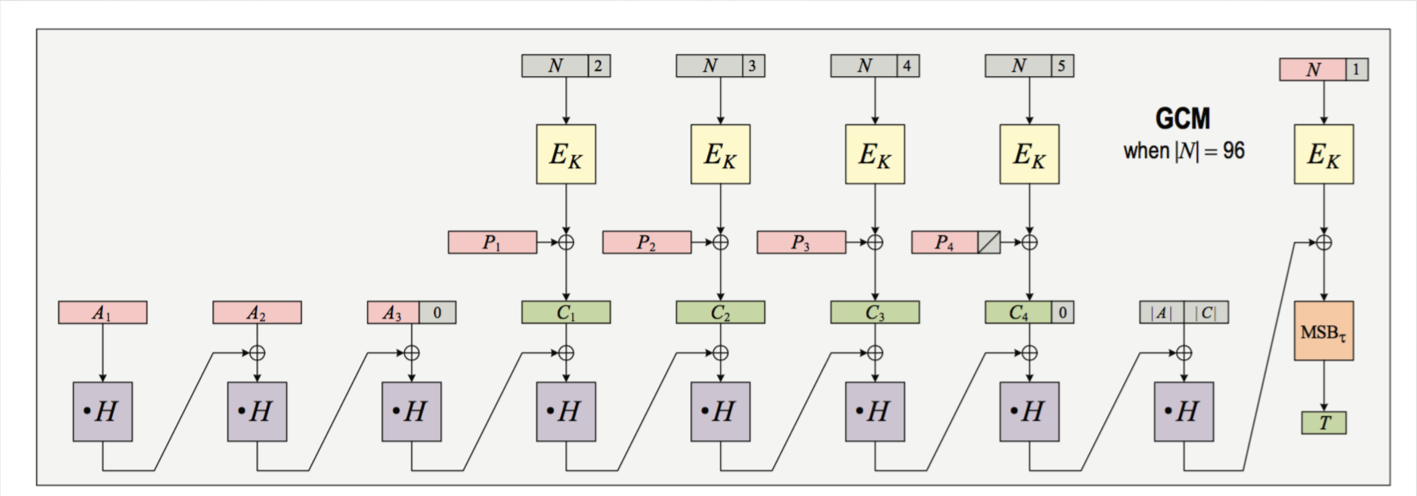
# Efficiency of GCM vs GCM-SIV

- **Encryption**
  - In **GCM**, CTR-ENC and GHASH are interleaved and run in parallel
  - In **GCM-SIV**, GHASH must be finished before CTR-ENC can begin **(cannot be done in parallel)**

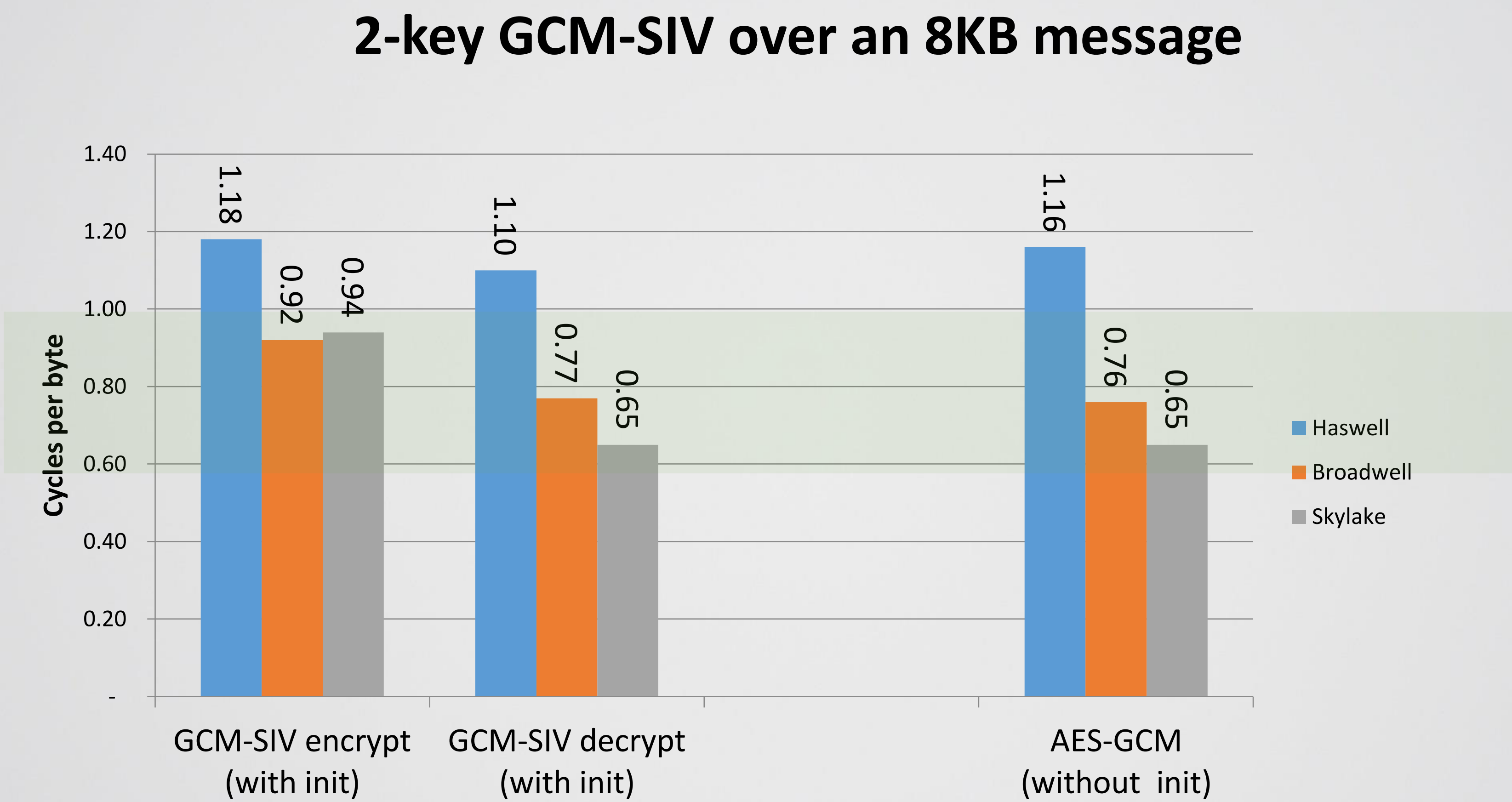


# Efficiency of GCM vs GCM-SIV

- **Decryption:**
  - In **GCM**, once again CTR-DEC and GHASH interleaved
  - In **GCM-SIV**, can also interleave (decryption cost "should be" the same as the original GCM)



# GCM-SIV Performance – Highlights



# Time Comparison to AES-GCM

- **GCM-SIV (our implementation) is faster than (OpenSSL's best) AES-GCM for short messages, due to a new software optimization**

| Full | | | | No Init | | |
|---|---|---|---|---|---|---|
| | Cycles | | | Cycles | | |
| HSW/BDW | GCM-SIV | GCM-SIV | AES-GCM | GCM-SIV | GCM-SIV | AES-GCM |
| # bytes | Two keys | One key | | Two keys | One key | |
| 16 | 149 / 136 | 297 / 241 | 1289 / 1263 | 133 / 121 | 133 / 121 | 178 / 172 |
| 32 | 198 / 171 | 318 / 284 | 1277 / 1318 | 178 / 153 | 178 / 153 | 219 / 217 |
| 64 | 322 / 281 | 444 / 417 | 1292 / 1335 | 319 / 278 | 319 / 278 | 236 / 238 |
| 128 | 516 / 440 | 645 / 568 | 1415 / 1371 | 282 / 262 | 282 / 262 | 293 / 266 |
| 256 | 674 / 566 | 800 / 694 | 1558 / 1417 | 426 / 401 | 426 / 401 | 421 / 385 |
| 512 | 966 / 796 | 1093 / 930 | 1808 / 1730 | 722 / 626 | 722 / 626 | 760 / 651 |
| 1,024 | 1566 / 1252 | 1695 / 1385 | 2312 / 2108 | 1315 / 1085 | 1315 / 1085 | 1252 / 989 |
| 1,536 | 2159 / 1713 | 2274 / 1843 | 2816 / 2416 | 1907 / 1544 | 1907 / 1544 | 1714 / 1305 |
| 2,048 | 2751 / 2171 | 2869 / 2300 | 3372 / 2842 | 2498 / 1996 | 2498 / 1996 | 2287 / 1765 |
| 4,096 | 5118 / 4005 | 5244 / 4136 | 5332 / 4354 | 4867 / 3837 | 4867 / 3837 | 4296 / 3243 |
| 8,192 | 9862 / 7666 | 9994 / 7782 | 9521 / 7388 | 9611 / 7498 | 9611 / 7498 | 8399 / 6289 |

| | C/B | | | C/B | | |
|---|---|---|---|---|---|---|
| 8,192 | 1.2/0.94 | 1.22/0.95 | 1.16/0.9 | 1.17/0.92 | 1.17/0.92 | 1.03/0.77 |

# GCM-SIV Performance Comparison

- **GCM-SIV significantly outperforms all other implemented nonce-misuse resistant schemes**
  - Including all CAESAR round 1 candidates
  - Based on published authors' optimized implementations
  - When measured on modern x64 processors
- **The only exception is AEZ, which is based on a non-standard use of AES**

# Summary

- Full nonce misuse-resistant authenticated encryption at an **extremely low cost** (almost AES-GCM)
- **Full proof of security** and **full implementation**
- **Easily deployable:**
  - Utilizes existing hardware
  - Utilize existing code and software (AES-GCM implementations)
- Detailed specifications, reference code and Open Source optimized code implementations coming soon
- Unpatented
- We hope to see it adopted

# Thank You