

Collision Attacks on Galois/Counter Mode (GCM)

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Abstract. Advanced Encryption Standard Galois/Counter Mode (AES-GCM) is the most widely used Authenticated Encryption with Associated Data (AEAD) algorithm in the world. In this paper, we analyze the use of GCM with all the Initialization Vector (IV) constructions and lengths approved by NIST SP 800-38D when encrypting multiple plaintexts with the same key. We derive attack complexities in both ciphertext-only and known-plaintext models, with or without nonce hiding, for collision attacks compromising integrity and confidentiality. Our analysis shows that GCM with random IVs provides less than 128 bits of security. When 96-bit IVs are used, as recommended by NIST, the security drops to less than 97 bits. Therefore, we strongly recommend NIST to forbid the use of GCM with 96-bit random nonces.

Keywords: Secret-key Cryptography · Block Ciphers · Cryptanalysis · Collision Attacks · AEAD · MAC · GCM · GMAC

1 Introduction

Galois/Counter Mode (GCM) is an Authenticated Encryption with Associated Data (AEAD) mode of operation, designed by McGrew and Viega [MV05] and standardized in NIST SP 800-38D [Dwo07]. GCM combines counter mode of encryption with Galois mode of authentication, which is a Wegman-Carter polynomial hash operating in the field $\text{GF}(2^{128})$. Originally designed for block ciphers with a 128-bit block size, such as the Advanced Encryption Standard (AES) [AES23], but as shown in [CMP23] it can also be adapted for use with any stream cipher like SNOW 5G [EJMY21] or Rijndael-256-256 [DR03] in counter mode.

AES-GCM is the most widely used AEAD algorithm in the world, used in numerous security protocols, including TLS [Res18], QUIC [TT21], IPsec [VM05], MACsec [MAC18], and WiFi WPA3 [WPA24]. It is also supported by many cryptographic APIs such as PKCS #11 [PKC20], Oracle Java SE [JAV24], Microsoft Cryptography API [CNG21], W3C Web Cryptography API [W3C17], the Linux Kernel Crypto API [Lin], and Apple CryptoKit [App]. Its popularity is well-deserved due to its strong performance and proven security [MV04, IOM12]. GCM is online, fully parallelizable, and can be efficiently pipelined, making it highly effective in both hardware and software, especially on processors with dedicated instructions to accelerate AES and GHASH [Gue23].

Weaknesses in GCM have been discussed by several researchers, including Ferguson [Fer05], Joux [Ant06], Handschuh and Preneel [HP08], Iwata et al. [IOM12], Saarinen [Saa11], Procter and Cid [PC15], Mattsson and Westerlund [MW15], Abdelraheem et al. [ABBT15], Forler et al. [FLLW17], and Luykx and Preneel [LP18]. An extensive evaluation of GCM was conducted by Rogaway [Rog11]. It is well-known that reusing a counter value, known as a two-time pad, compromises confidentiality. Furthermore, Joux demonstrated that reusing a single Initialization Vector (IV) in GCM also breaks integrity [Ant06]. NIST has decided to revise NIST SP 800-38D [Ann24]. The proposed

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changes include removing support for authentication tags shorter than 96 bits, as suggested by [Rog11, MW15], and providing clearer guidance on IV constructions. NIST has not provided any additional details except that it will clarify that the IV construction used in TLS 1.3 [Res18] is approved.

In this paper, we analyze the use of GCM with all the IV constructions and lengths approved in NIST SP 800-38D [Dwo07] when encrypting multiple plaintexts with the same key. We derive attack complexities in both ciphertext-only and known-plaintext models, with or without nonce hiding [BNT19], for collision attacks compromising integrity and confidentiality. The confidentiality attacks enable the attacker to find a large number of colliding keystream blocks and are therefore significantly more severe than distinguishing attacks [IOM12]. Our analysis shows that GCM with random IVs provides less than 128 bits of security. When 96-bit IVs are used, as recommended by NIST, the security drops to less than 97 bits. Users of AES-GCM expect 128, 192, or 256 bits of security. Therefore, we strongly recommend that NIST revise SP 800-38D to forbid the use of GCM with 96-bit random nonces. Our analysis shows that nonce hiding [BNT19] requires collision attacks to be performed in known-plaintext instead of ciphertext-only but does not otherwise affect attack complexity. The integrity attacks on GCM also apply to Galois Message Authentication Code (GMAC) [Dwo07]. Furthermore, many of the attacks are generic and affect other AEAD algorithms, such as Counter with Cipher Block Chaining-Message Authentication Code (CCM) [Dwo04] and ChaCha20-Poly1305 [NL18], when they are used with random nonces.

2 Collision Attacks on Galois Counter Mode (GCM)

In this section, we analyze GCM as specified in NIST SP 800-38D [Dwo07]. For simplicity, we assume the block cipher is AES [AES23], the only NIST-approved block cipher. Given an AES algorithm and key K , the authenticated encryption function takes three input strings: plaintext P , additional authenticated data A , and initialization vector IV . The output consists of ciphertext C and authentication tag T .

The AES key length can be 128, 192, or 256 bits, while the block size is always 128 bits, regardless of key size. The plaintext must be shorter than $2^{32} - 2$ 16-byte blocks. The IV length must be between 1 and $2^{61} - 1$ bytes, though NIST recommends that implementations restrict support to 96-bit IVs. NIST SP 800-38D specifies two IV constructions: one deterministic and one based on a Random Bit Generator (RBG). For IVs shorter than 96 bits, the deterministic construction must be used, while for IVs equal to or longer than 96 bits, either construction is permissible:

- In the deterministic construction, the IV is the concatenation of two fields: the fixed field and the invocation field. For any given key, no two distinct devices shall share the same fixed field, and no two distinct sets of inputs to any single device shall share the same invocation field. Typically, the invocation field is an integer counter.
- In the RBG-based construction, the IV is the concatenation of two fields: the random field, which must be at least 96 bits long, and the free field, which has no specific requirements. For our analysis, we assume the free field is empty, meaning the length of the random field equals $|IV|$, the length of the initialization vector in bits. The random field must either consist of the output from an approved RBG or result from applying the incrementing function modulo $2^{|IV|}$ to the random field of the previous IV for the given key. The output string from the RBG is called a direct random string, and the random fields that result from applying the incrementing function are called its successors.

Unless an implementation exclusively uses 96-bit IVs generated by the deterministic

construction, the number of invocations of the authenticated encryption function must not exceed 2^{32} for a given key.

The GCM authenticated encryption function is detailed in Section 7.1 of NIST SP 800-38D [Dwo07]. The steps relevant to our analysis are:

$$H = \text{AES-ENC}(K, 0^{128})$$

$$\text{If } |IV| = 96, \text{ then } J_0 = IV \parallel 0^{31} \parallel 1$$

$$\text{If } |IV| \neq 96, \text{ then } J_0 = \text{GHASH}(H, IV \parallel \dots)$$

$$J_0 = F \parallel I \text{ where } F \text{ is the leftmost 96 bits, and } I \text{ is the rightmost 32 bits}$$

$$J_1 = F \parallel (I + 1) \pmod{2^{32}}$$

$$C_i = \text{AES-ENC}(K, J_{i+1}) \oplus P_i$$

$$T = \text{AES-ENC}(K, J_0) \oplus \dots$$

where “...” indicates data not relevant to our analysis. The steps assume a tag length of 128 bits and a plaintext length that is a multiple of 16 bytes. P_i and C_i denote the i -th block in the plaintext and ciphertext, respectively.

We analyze the security of AES-GCM across all approved IV constructions and lengths specified in NIST SP 800-38D [Dwo07] when encrypting multiple plaintexts with the same key K . Specifically, we derive concrete complexities of collision attacks finding collisions between initialization vectors IV or between counter values J in different AES-GCM invocations under the same key. Our attacks do not assume any flaws in the random bit generator or GHASH, remaining effective even if their behavior is indistinguishable from a truly random function. IV collision attacks on GCM were briefly mentioned in [PST23, PST24], but only in the context of ciphertext-only attacks on the RBG-based construction with 96-bit IVs.

It is evident that no collisions occur between counter values within a single invocation. In the following, we use the notation IV_k for the initialization vector in invocation k and J_{ik} for the counter value J_i in invocation k . A collision where $IV_k = IV_l$ implies $J_{0k} = J_{0l}$. A collision $J_{0k} = J_{0l}$ (where $k \neq l$) compromises both integrity and confidentiality. A collision $J_{ik} = J_{jl}$ (where $k \neq l$ and i and j are not both being 0) compromises confidentiality but not integrity.

2.1 Deterministic Construction with $|IV| = 96$ bits

When the deterministic construction is used with 96-bit IVs, collisions between IVs and counter values across different invocations do not occur. That is, $IV_k \neq IV_l$ when $k \neq l$, and $J_{ik} \neq J_{jl}$ when $i \neq j$ or $k \neq l$. Hence, collision attacks are not feasible under these conditions.

2.2 RBG-Based Construction with $|IV| = 96$ bits

Assuming the free field is empty, when using r direct random cleartext IVs with $|IV| = 96$ bits and no successors under the same key, the probability of an IV collision is $\approx r^2/2^{97}$. An IV collision $IV_k = IV_l$ where $k \neq l$ implies $J_{0k} = J_{0l}$, compromising both confidentiality and integrity. An attacker can detect collisions among r cleartext IVs with work $\approx r$ using a hash table. Thus, the time complexity of a collision attack is $\approx r/(r^2/2^{97}) = 2^{97}/r$, and the security is only $\approx 97 - \log_2 r$. The memory and data complexities are $\mathcal{O}(r)$.

Assume instead that r direct random strings are used, each followed by $m - 1$ successors obtained by incrementing the random field of the previous IV modulo $2^{|IV|}$. The number

of IVs is $n = rm$. The probability that two IVs collide is $\approx (mr^2/2^{97})$. The work required is $\approx mr$, and the security remains $\approx 97 - \log_2 r$.

Once hiding techniques [BNT19], such as those employed in DTLS 1.3 [RTM22] and QUIC [TT21], transform the collision attack from ciphertext-only to known-plaintext. In these protocols, the IV transmitted over the network is encrypted by XORing with AES-ENC(K_2, C_0), where K and K_2 are derived from the same secret. If the attacker knows 16 bytes P_i of the plaintext, they can identify collisions by hashing all $P_i \oplus C_i$. Moreover, if the first 16 bytes of the plaintext constitute a fixed header (see, e.g., Section 3.4 of [Pre23]), the attacker can detect collisions by hashing the encrypted IVs. The security remains $\approx 97 - \log_2 r$.

2.3 Deterministic Construction with $|\text{IV}| \neq 96$ bits

In the deterministic construction, collisions between the IVs are not possible. However, since each IV_k is hashed to produce a 128-bit value J_{0k} , collisions can occur between different counter values, meaning $J_{ik} = J_{jl}$ where $k \neq l$.

The probability that $J_{0k} = J_{0l}$ for $k \neq l$ is $\approx n^2/2^{129}$. Such collisions compromise both confidentiality and integrity. An attacker can find such a collision with work $\approx n$, assuming a fixed header. Consequently, the security against this type of attack is $\approx 129 - \log_2 n$.

A collision $J_{ik} = J_{jl}$ where $k \neq l$ and i and j are not both 0 does not break integrity but does compromise confidentiality. Assuming the plaintexts are 2^{31} blocks or larger, the probability that at least two different counter values collide is $\approx n^2/2^{97}$. If $J_{ik} = J_{jl}$, then likely $J_{(i+1)k} = J_{(j+1)l}$ where the addition is modulo 2^{32} . This results in the keystreams $P \oplus C$ in invocations k and l being partially identical. The work for an attacker to find such a collision is $\approx n \cdot 2^{31}$, as they only need to test the first $\approx 2^{31}$ blocks. The security against this attack is $\approx 128 - \log_2 n$. One assumption in this scenario could be that the plaintexts consist of $\approx 2^{32}$ blocks, with the attacker knowing the first half of the plaintexts but not the second half.

If the plaintexts have the length $s < 2^{31}$, the probability that at least two different counter values collide is $\approx (n^2/2^{97})(2s/2^{32}) = sn^2/2^{128}$. The work required is $\approx ns$, and the security is $\approx 128 - \log_2 n$. One assumption in this scenario could be that the attacker knows most, but not all, of the plaintext.

2.4 RBG-based construction with $|\text{IV}| > 96$ bits

Assuming the free field is empty, when using r direct random cleartext IVs with the same key, the probability of an IV collision is $\approx r^2/2^{|\text{IV}|+1}$. Such a collision compromises both confidentiality and integrity. The attacker's work is $\approx r$ and the security is $\approx |\text{IV}| + 1 - \log_2 r$.

Since each IV_k is hashed to produce a 128-bit value J_{0k} , there might be collisions $J_{0k} = J_{0l}$ even if $IV_k \neq IV_l$. The probability for such a collision compromises both confidentiality and integrity is $\approx r^2/2^{129}$. The total probability that $J_{0k} = J_{0l}$ where $k \neq l$ is $\approx r^2/2^{|\text{IV}|+1} + r^2/2^{129}$. The work required for an attacker to find such a collision is $\approx r$ (assuming fixed header). If $|\text{IV}| = 128$, the security against this attack is $\approx 128 - \log_2 r$. For $|\text{IV}| \neq 128$, the security is $\approx \min(129, |\text{IV}| + 1) - \log_2 r$.

A collision $J_{ik} = J_{jl}$ where $k \neq l$ and i and j are not both 0 does not break integrity but does compromise confidentiality. Assuming the plaintexts are 2^{31} blocks or larger, the probability that at least two different counter values collide is $\approx r^2/2^{97}$. If $J_{ik} = J_{jl}$ then likely $J_{(i+1)k} = J_{(j+1)l}$ where the addition is modulo 2^{32} . This results in the keystreams $P \oplus C$ in invocations k and l being partially identical. The work for an attacker to find such a collision is $\approx r \cdot 2^{31}$, as they only need to test the first 2^{31} blocks. The security against this attack is $\approx 128 - \log_2 r$. As before, we can extend the attack to apply to $s < 2^{31}$,

with the same complexity. If $|IV| < 128$, the attacker will first search for IV collisions, resulting in a security level of $\approx \min(128, |IV| + 1) - \log_2 r$.

2.5 Summary

The security of GCM against collision attacks is summarized in Tables 1, 2, and 3. Table 1 summarizes the security against ciphertext-only collision attacks that compromise integrity and confidentiality. Table 2 shows the security against known-plaintext collision attacks that compromise integrity. Finally, Table 3 details the security against known-plaintext collision attacks that compromise confidentiality. Note that the attacks in Table 2 also compromise confidentiality. However, for certain parameters, the attacks in Table 3 are slightly more effective for an attacker focused solely on compromising confidentiality.

Table 1: Security against ciphertext-only collision attacks breaking integrity and confidentiality. $n \leq 2^{32}$ is the number of IVs. $r = n/m$ is the number of direct random strings.

| | $ IV < 96$ | $ IV = 96$ | $ IV > 96$ |
|---------------|-------------|-------------------------|-------------------------------|
| Deterministic | ∞ | ∞ | ∞ |
| RBG-based | N/A | $\approx 97 - \log_2 r$ | $\approx IV + 1 - \log_2 r$ |

Table 2: Security against known-plaintext collision attacks breaking integrity. $n \leq 2^{32}$ is the number of IVs. $r = n/m$ is the number of direct random strings. When $|IV| = 128$, a more accurate estimate for the security of the RBG-based construction is $\approx 128 - \log_2 r$.

| | $ IV < 96$ | $ IV = 96$ | $ IV > 96$ |
|---------------|--------------------------|-------------------------|--|
| Deterministic | $\approx 129 - \log_2 n$ | ∞ | $\approx 129 - \log_2 n$ |
| RBG-based | N/A | $\approx 97 - \log_2 r$ | $\approx \min(129, IV + 1) - \log_2 r$ |

Table 3: Security against known-plaintext collision attacks breaking confidentiality. $n \leq 2^{32}$ is the number of IVs. $r = n/m$ is the number of direct random strings.

| | $ IV < 96$ | $ IV = 96$ | $ IV > 96$ |
|---------------|--------------------------|-------------------------|--|
| Deterministic | $\approx 128 - \log_2 n$ | ∞ | $\approx 128 - \log_2 n$ |
| RBG-based | N/A | $\approx 97 - \log_2 r$ | $\approx \min(128, IV + 1) - \log_2 r$ |

3 Analysis of Algorithm and Protocol Specifications

Section 8 of NIST SP 800-38D [Dwo07] states the following regarding IV “uniqueness”:

“The probability that the authenticated encryption function ever will be invoked with the same IV and the same key on two (or more) distinct sets of input data shall be no greater than 2^{-32} .”

“The total number of invocations of the authenticated encryption function shall not exceed 2^{32} , including all IV lengths and all instances of the authenticated encryption function with the given key.”

NIST does not provide a motivation for the probability limit. Expressing requirement as probabilities has several issues. First, it assumes that users understand the complexities of birthday attack formulas and can calculate that a probability of 2^{-32} corresponds to $\approx (|IV| - 31)/2$ invocations. Additionally, achieving a probability of 2^{-32} is actually impossible with 2^{32} truly random 96-bit IVs. Our analysis shows that with a probability of 2^{-33} , a ciphertext-only attack compromising both integrity and confidentiality requires only time $T = 2^{65}$ and memory and data $M = D = 2^{32}$. Moreover, probability is not directly related to attack complexity; it only establishes a lower bound on security. This makes it unclear what security level NIST intended the requirement to provide. Furthermore, as Rogaway states Section 12.4.10 of [Rog11]:

*“the exposition in the NIST spec seems to kind of “fall apart” in Sections 8 and 9, and in Appendix C. These sections stray from the goal of defining GCM, and make multiple incorrect or inscrutable statements. Here are some examples. Page 18 : **The probability that the authenticated encryption function ever will be invoked with the same IV and the same key on two (or more) sets of input data shall be no greater than 2^{-32}** (here and later in this paragraph, imperatives are preserved in their original bold font). The probabilistic demand excludes use of almost all cryptographic PRGs (including those standardized by NIST), where no such guarantee is known.”*

Theoretically, using a cryptographic pseudorandom generator (PRG) for generating a large number of non-colliding IVs is the wrong approach. Instead, a pseudorandom function family (PRF) should be utilized. While a PRG ensures that a single output appears random, a PRF guarantees that all outputs appear random. The Double-Nonce-Derive-Key-GCM (DNDK-GCM) construction [Gue24] effectively uses a PRF.

3.1 Protocols and Other Algorithms

Many IETF protocols use the NIST-standardized version of GCM [Dwo07] with a deterministic construction and an IV length of 96 bits and do therefore not suffer from collision attacks. The exceptions are JOSE [Jon15] and COSE [Sch22], which may use random IVs, IPsec [VM05], which uses the pre-standardized version of GCM [MV05], and CMS [Hou07], which may use all IVs constructions and lengths allowed by NIST.

The collision attacks on GCM compromising confidentiality also apply to GMAC, which is also standardized in NIST SP 800-38D [Dwo07]. The ciphertext-only collision attacks listed in Table 1 also apply to CCM [32] and ChaCha20-Poly1305 [33] if used with random nonces. CCM with random nonces would be particularly problematic as it can be used with 7–13 byte nonces. In SP 800-38C NIST states that “The nonce is not required to be random”, suggesting that AES-CCM with random nonces is NIST-approved. Unlike for GCM, NIST does not mandate any specific nonce constructions, maximum collision probabilities, or maximum number of invocations. The security of AES-CCM with random nonces would be $\approx |IV| + 1 - \log_2 r$ where $|IV|$ can be as low as 56 and r can be as large as $\approx 2^{59}$. SP 800-38C only restricts the number of block cipher invocations:

“The total number of invocations of the block cipher algorithm during the lifetime of the key shall be limited to 2^{61} .”

As stated in Section 11.9 of [Rog11], Rogaway and Fergusson suggest that “The nonce is not required to be random” should be interpreted as the nonce need not be unpredictable. It is likely this was NIST’s intention. However, we do not believe this is how the statement will be understood by developers and users.

4 Conclusions and Recommendations

Without counter value collisions $J_{0k} = J_{0l}$ where $k \neq l$, the security against forgeries in GCM and GMAC is $\approx 2^{129}/\ell$ where ℓ is the plaintext length in blocks. For short plaintexts, the forgery probability is $\approx 2^{128}$, and for maximum length plaintexts the forgery probability is $\approx 2^{97}$. As shown in Table 1 and 2, the RBG-based construction significantly lowers security against forgeries. The attack model is practically serious, as it can be executed by passively observing communications, performing calculations offline, and if successful, allowing any number of forgeries with a success probability of 1.

Without counter value collisions $J_{ik} = J_{jl}$ where $k \neq l$, the best attacks on AES-GCM confidentiality are distinguishing attacks based on the birthday bound. With counter value collisions, collision attacks finding colliding parts of keystream (two-time pad) becomes possible. As shown in Table 1 and 3, the security of the RBG-based construction significantly lowers security even when $r = 2$.

We strongly recommend that NIST disallow the use of the RGB-construction when $|IV| < 128$, as it significantly lowers the security against forgeries for all plaintext lengths. Additionally, NIST should consider disallowing the RGB-construction when $|IV| \geq 128$ as it significantly lowers the security against forgeries for short plaintext lengths. We also advise NIST to disallow the use of the deterministic construction when $|IV| \neq 96$, as it lowers security and there is no reason to ever use it. NIST should ensure that all remaining options achieve security strength of 128 bits [KEY20] and clearly describe the security strength category [KEM23] of each option.

If NIST intends to continue allowing the RBG-based construction, given the potential use cases for AES-GCM with random IVs, we recommend that NIST mandate that the random field is at least 17 bytes and clearly state the security level against collision attacks. NIST should recommend or mandate minimizing the use of direct random strings, ideally limiting it to one per device. While GCM with non-96-bit IVs has other theoretical weaknesses [ABBT15], to our knowledge, none are remotely comparable to ciphertext-only attacks that break integrity and confidentiality with complexity $2^{97}/r$.

If the RBG-based construction is kept, NIST should replace the probability-based IV requirement with an explicit requirement that is easy to understand for developers and users. This requirement should clearly specify the number of authenticated encryption invocations with the same key for different lengths of the random field. NIST should also give examples of PRGs or PRFs that can be used for generating a large number of non-colliding IVs. A better solution than using the RBG-based construction is likely deriving a new key K for each random nonce as suggested in DNDK-GCM [Gue24].

We strongly recommend that NIST and IETF explicitly disallow the use of the random nonces in AES-CCM and ChaCha20-Poly1305. Additionally, we suggest that NIST update the terminology in SP 800-38D to use “nonce” instead of “IV”, as “nonce” is now the established term for the AEAD input parameter [McG08], while “IV” commonly refers to one of the fields used to construct the nonce [Res18, VM05]. Updating SP 800-38D to use the term “nonce” will align it with SP 800-38C. We recommend IETF to update the use of GCM in IPsec [VM05] to refer to the standardized version of GCM [Dwo07].

Future AEAD schemes should use 256-bit keys and 256-bit nonces. Shorter nonces could be acceptable for misuse-resistant AEs (MRAE) [RS06] as nonce collisions only lowers the security to DAE (deterministic authenticated encryption). Robust AE (RAE) [HKR14] are especially attractive as they combine misuse-resistance with reforgeability resilience. However, as interfaces should be designed to minimize user demands and mitigate the consequences of human errors [Gui16], users ideally should not have to handle nonces. Consequently, we believe that future standardized authenticated encryption interfaces should not require nonces as input. One such interface is AERO [MF14, Min15], which not only manages nonces but also provides replay protection and nonce hiding.

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