Combinatorial Coverage Measurement of Test Vectors used in Cryptographic Algorithm Validation

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Overview

- Measuring the combinatorial coverage of test vectors used in the Cryptographic Algorithm Validation Program (CAVP).
- Using differential testing and golden model testing in tandem to identify incorrect behavior in the context of multiple AES implementations tested together.

CAVP

- The Cryptographic Algorithm Validation Program (CAVP) encompasses validation testing for FIPS-approved and NIST recommended cryptographic algorithms.
- It was established by NIST and the Communications Security Establishment Canada (CSEC) in July 1995.
- It currently validates implementations of the following cryptographic algorithms: AES, TDES, Skipjack, DSA, ECDSA, RSA, SHA, RNG, DRBG, KAS, CMAC, CCM, HMAC, GCM, and GMAC.

AES Validation Testing

- NIST developed a set of tests, referred to as the AES Validation test suite, to ensure the quality and correctness of AES implementations.
- The AES Algorithm Validation System (AESAVS) specifies validation testing requirements for the ECB, CBC, OFB, CFB, and CTR modes for the AES algorithm.
- If a vendor’s AES implementation successfully passes all the tests, NIST issues an AES Validation certificate to the vendor.

Modeling of Test Vectors

- We map existing test vectors into discrete parameters and values that can be analyzed and evaluated using coverage measurement tools.
- Assume that we perform a cryptographic operation (e.g. encryption, decryption) using cryptographic keys of either 128, 192, or 256 bits.
- The Input Parameter Model (IPM) for our combinatorial coverage measurement problem consists of 128, 192, or 256 binary parameters corresponding to cryptographic keys.

Combinatorial Coverage of CAVP Tests

- We use the Combinatorial Coverage Measurement (CCM) tool to measure the combinatorial coverage of the AES KAT Vectors, AES MCT Sample Vectors, AES MCT Intermediate Values, and AES MMT Sample Vectors.

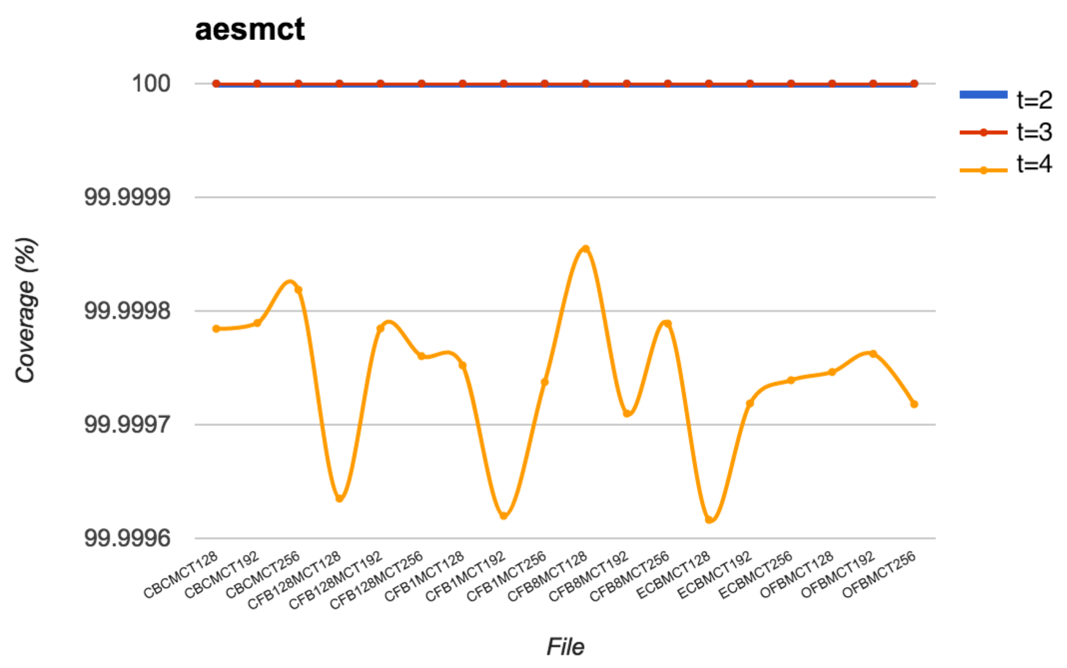
- Our model contains either 128, 192, or 256 binary parameters.

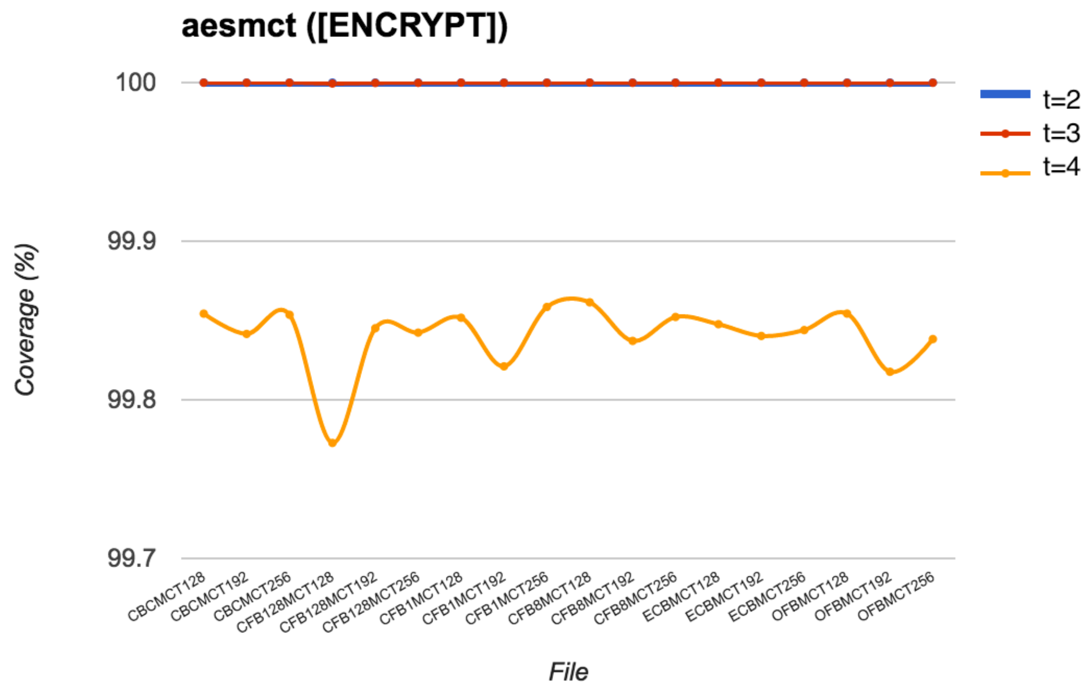
- The combinatorial coverage refers to 2-way, 3-way, and 4-way coverage.

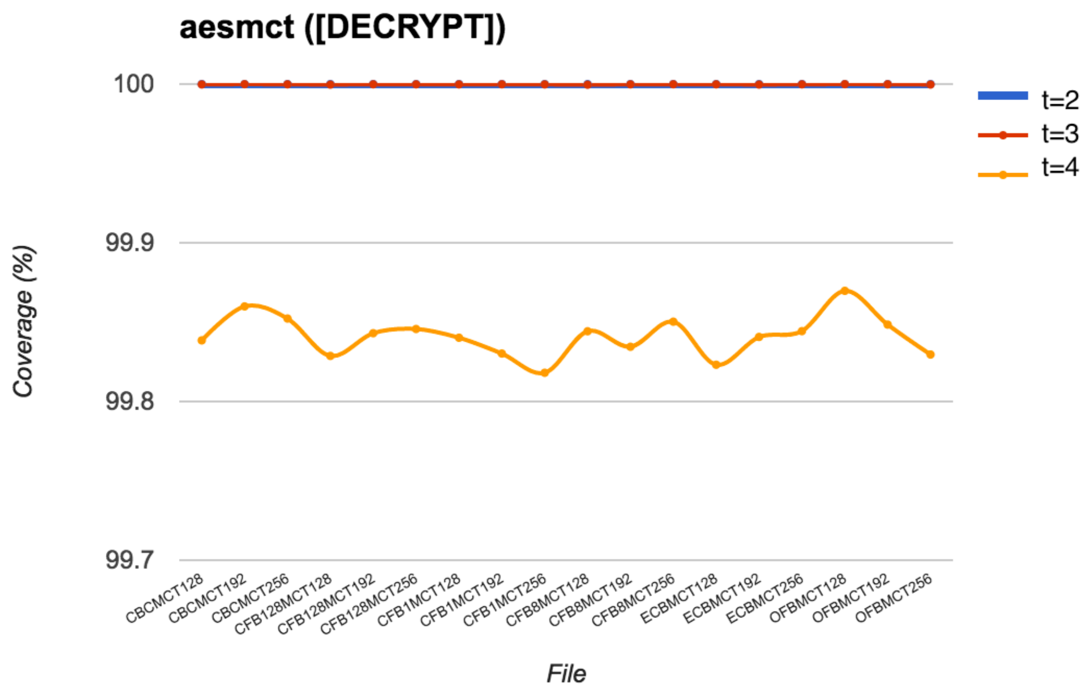
- A test set consists of either test vectors which are properly formatted in response (.rsp) files or files with intermediate results (.txt) which are supplied to help with debugging.
- Each file contains cryptographic keys grouped with other cryptographic information (e.g. plaintexts, initialization vectors, ciphertexts).
- The filename contains information about the test set and the key length (e.g. 128, 192, 256 bits).

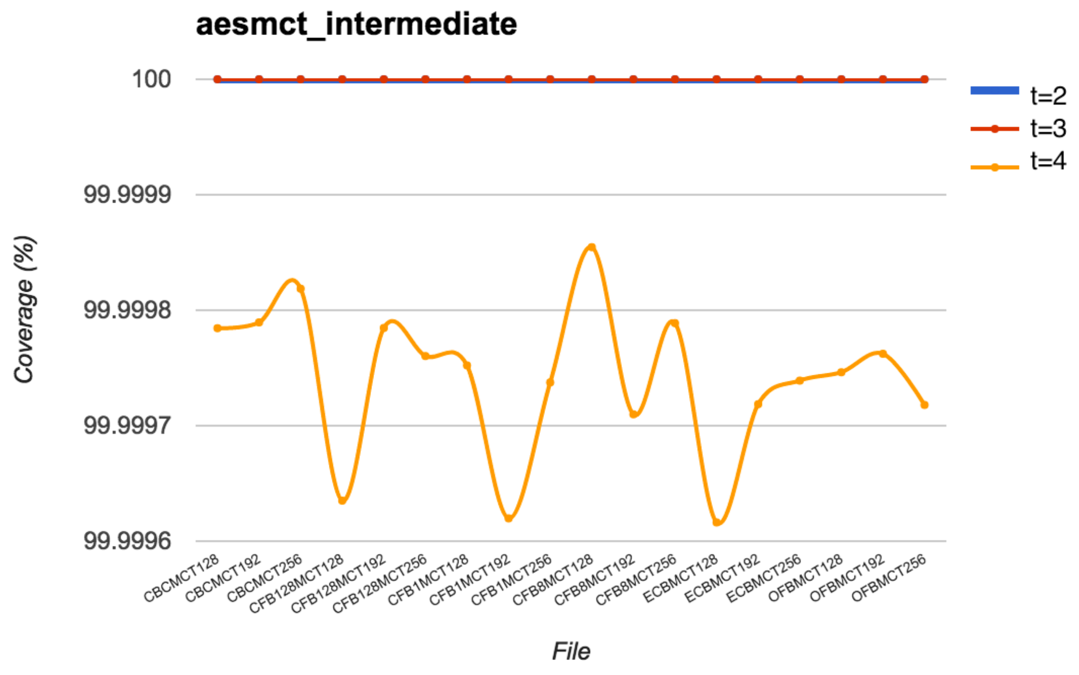
Measurement Results

- We measured the total 2-way through 4-way coverage considering
  - all keys for both encryption of plaintext and decryption of ciphertext,
  - only encryption keys, and
  - only decryption keys.


aesmct
100
99.9999
99.9998
99.9997
99.9996
Coverage (%)
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
CFB8MCT192
CFB8MCT256
ECBMCT128
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256
File


aesmct ([ENCRYPT])
100
99.9
99.8
99.7
Coverage (%)
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
CFB8MCT192
CFB8MCT256
ECBMCT128
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256
File


aesmct ([DECRYPT])
100
99.9
99.8
99.7
Coverage (%)
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
CFB8MCT192
CFB8MCT256
ECBMCT128
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256
File


aesmct_intermediate
100
99.9999
99.9998
99.9997
99.9996
Coverage (%)
File
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
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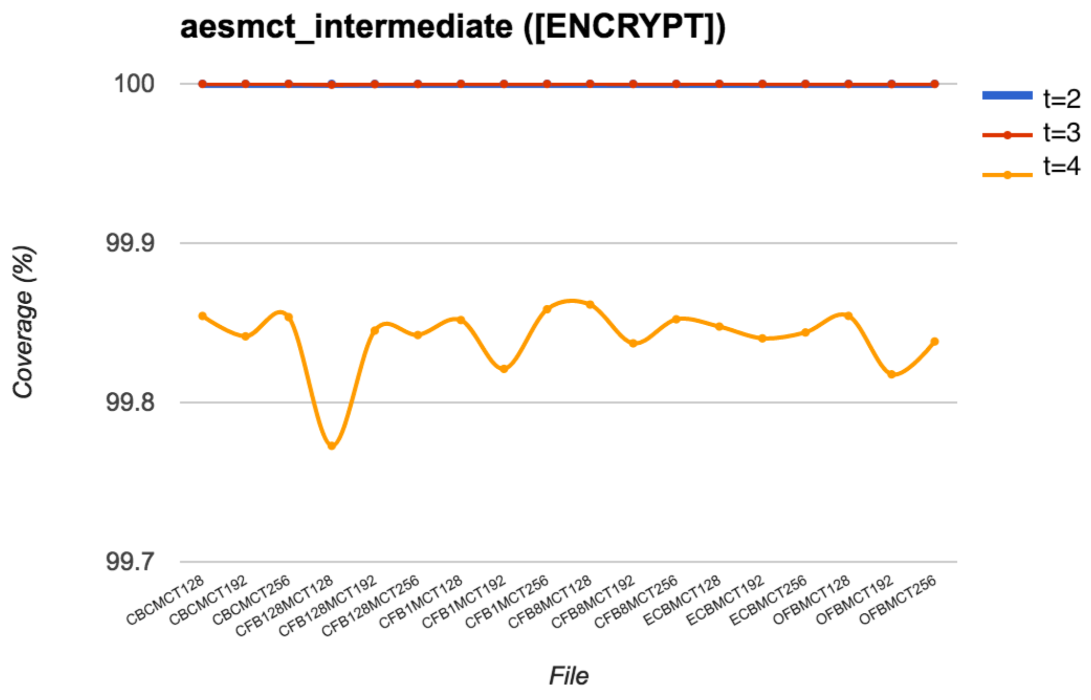
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256


aesmct_intermediate ([ENCRYPT])
100
99.9
99.8
99.7
Coverage (%)
File
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
CFB8MCT192
CFB8MCT256
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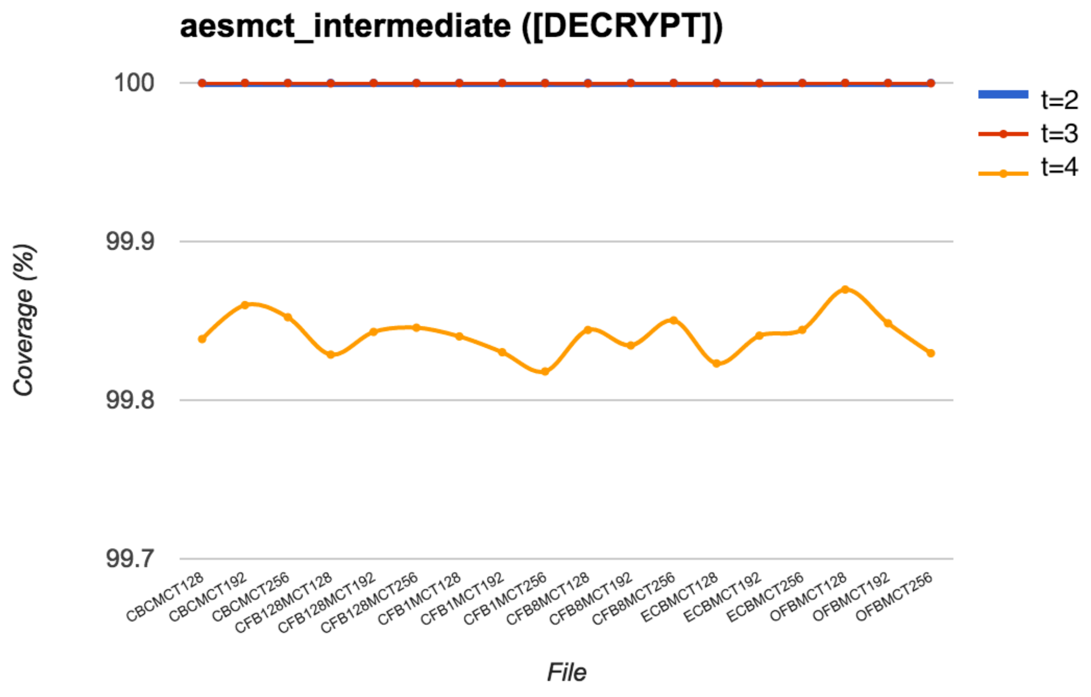
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256


aesmct_intermediate ([DECRYPT])
100
99.9
99.8
99.7
Coverage (%)
File
t=2
t=3
t=4
CBCMCT128
CBCMCT192
CBCMCT256
CFB128MCT128
CFB128MCT192
CFB128MCT256
CFB1MCT128
CFB1MCT192
CFB1MCT256
CFB8MCT128
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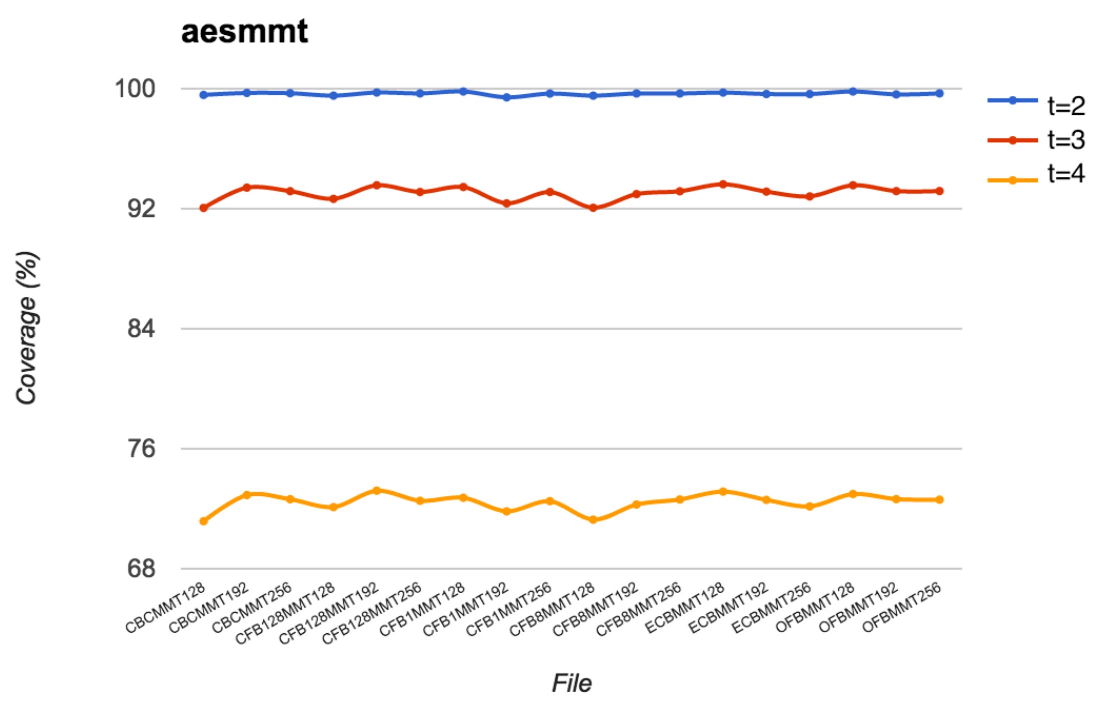
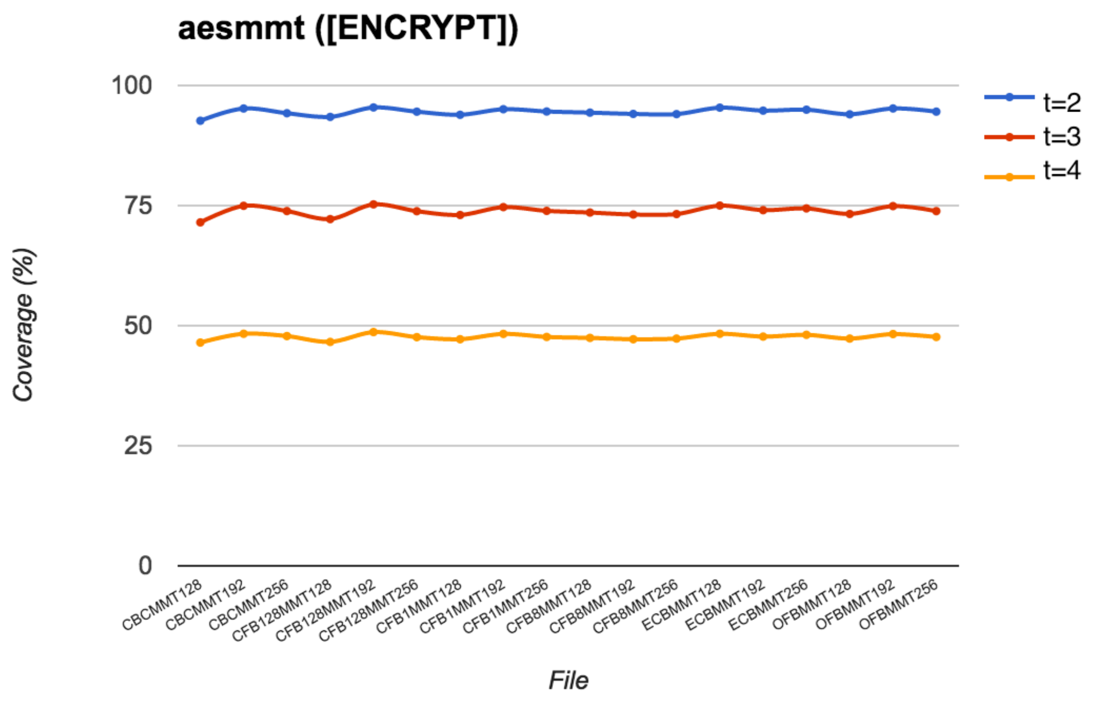
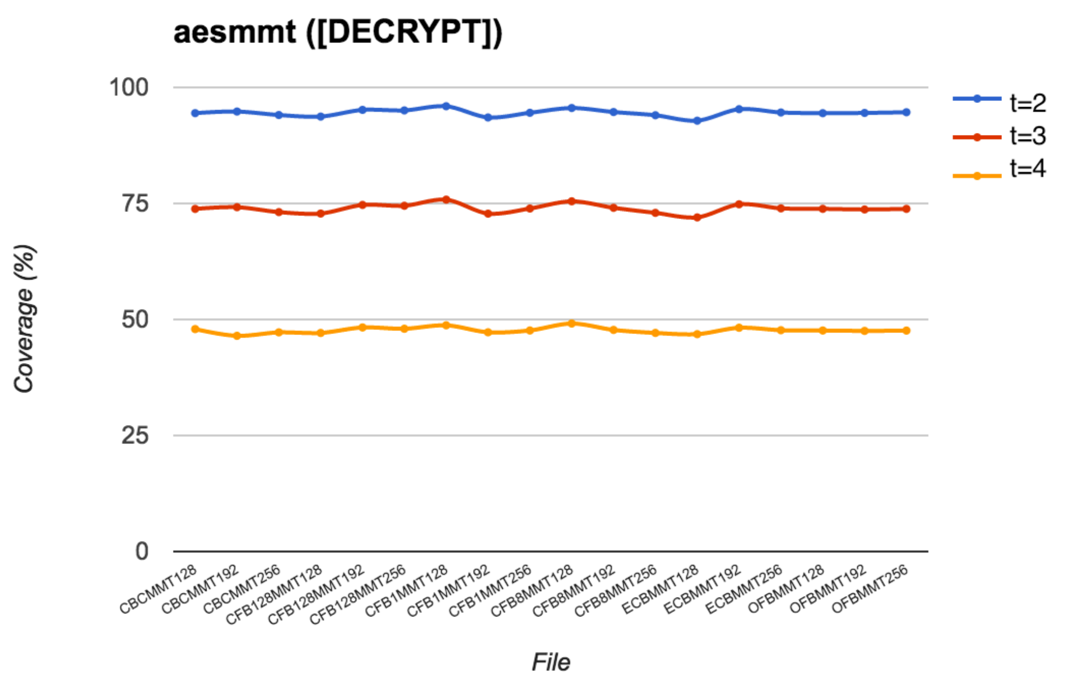
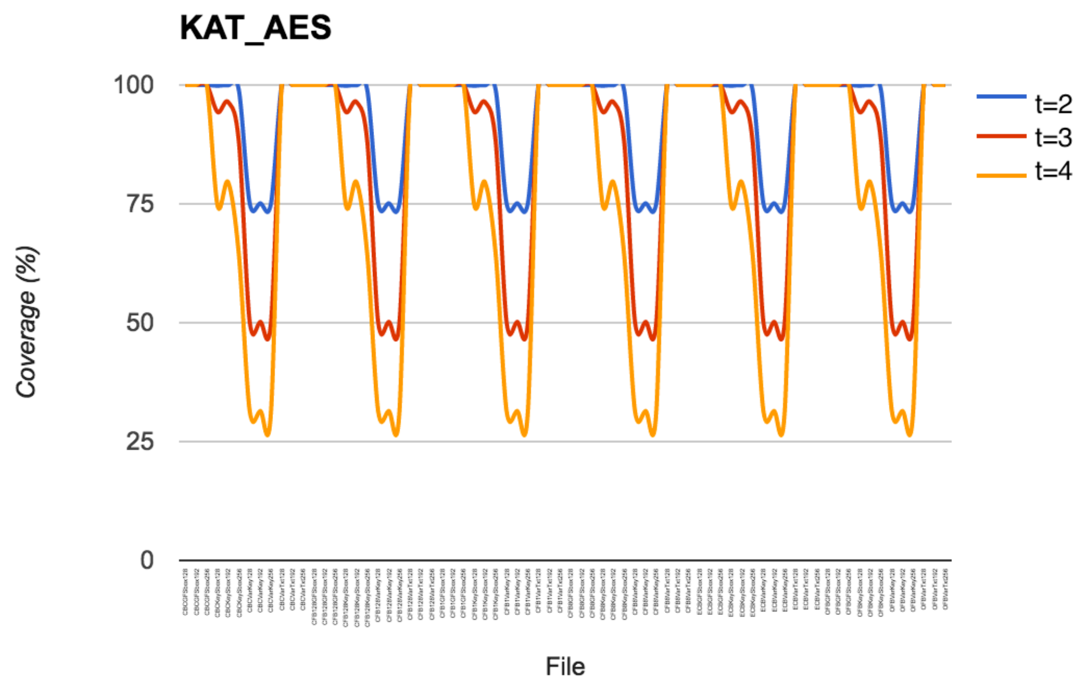
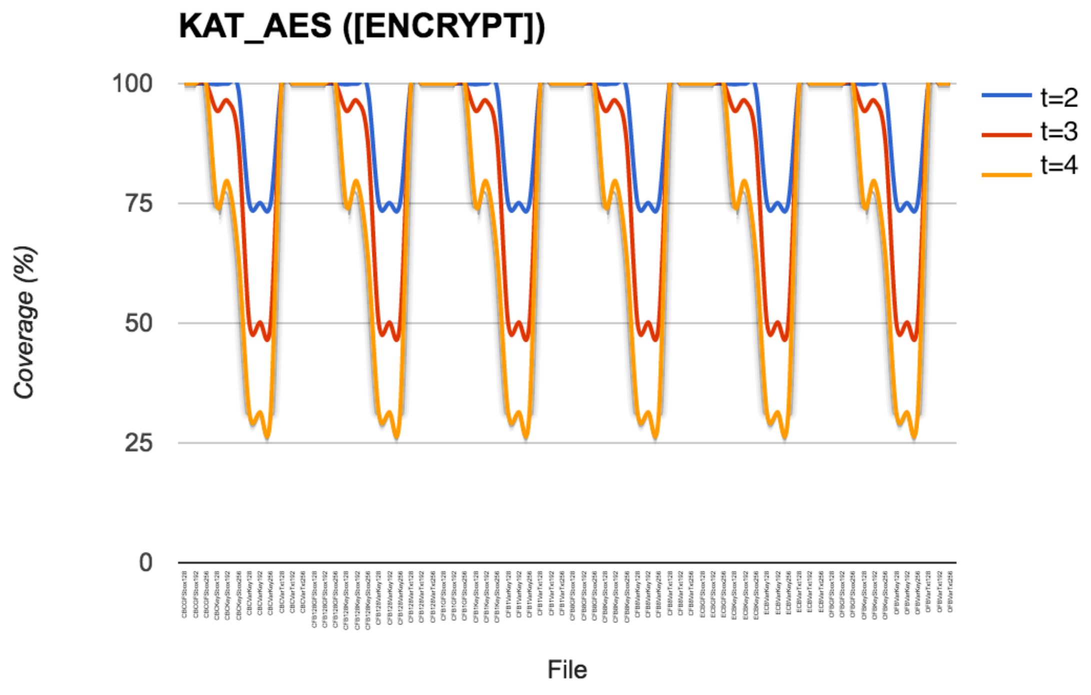
CFB8MCT256
ECBMCT128
ECBMCT192
ECBMCT256
OFBMCT128
OFBMCT192
OFBMCT256

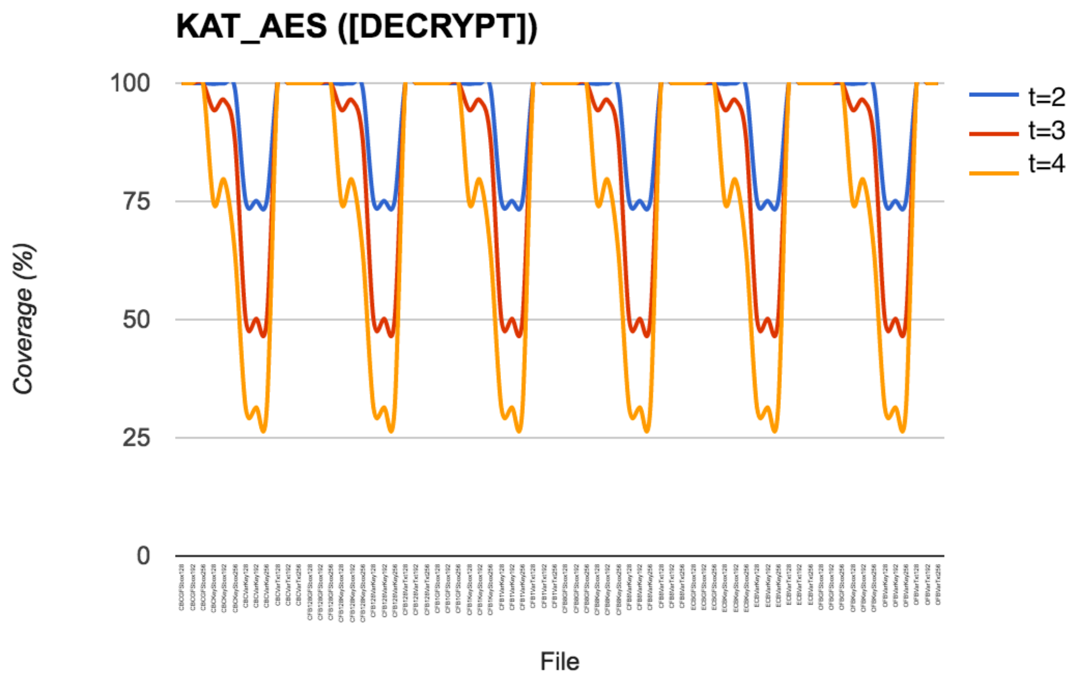

aesmmt
100
92
84
76
68
Coverage (%)
t=2
t=3
t=4
CBCMMT128
CBCMMT192
CBCMMT256
CFB128MMT128
CFB128MMT192
CFB128MMT256
CFB1MMT128
CFB1MMT192
CFB1MMT256
CFB8MMT128
CFB8MMT192
CFB8MMT256
ECBMMT128
ECBMMT192
ECBMMT256
OFBMMT128
OFBMMT192
OFBMMT256
File


aesmmt ([ENCRYPT])
100
75
50
25
0
Coverage (%)
t=2
t=3
t=4
CBCMMT128
CBCMMT192
CBCMMT256
CFB128MMT128
CFB128MMT192
CFB128MMT256
CFB1MMT128
CFB1MMT192
CFB1MMT256
CFB8MMT128
CFB8MMT192
CFB8MMT256
ECBMMT128
ECBMMT192
ECBMMT256
OFBMMT128
OFBMMT192
OFBMMT256
File


aesmmt ([DECRYPT])
100
75
50
25
0
Coverage (%)
t=2
t=3
t=4
CBCMMT128
CBCMMT192
CBCMMT256
CFB128MMT128
CFB128MMT192
CFB128MMT256
CFB1MMT128
CFB1MMT192
CFB1MMT256
CFB8MMT128
CFB8MMT192
CFB8MMT256
ECBMMT128
ECBMMT192
ECBMMT256
OFBMMT128
OFBMMT192
OFBMMT256
File


KAT_AES
Coverage (%)
100
75
50
25
0
File
t=2
t=3
t=4


KAT_AES ([ENCRYPT])
Coverage (%)
100
75
50
25
0
File
t=2
t=3
t=4


KAT_AES ([DECRYPT])
Coverage (%)
100
75
50
25
0
File
t=2
t=3
t=4

Implication for Testing

- In some cases, the AES test vectors do not achieve a full 2-way to 4-way combinatorial coverage.
- If 90% - 100% of the relevant state space has been covered, then presumably the risk is small, but if coverage is much smaller, then the risk may be substantial.
- Using the CCM tool we generated all missing combinations to achieve full coverage for t=2.
- It entails making certain that the necessary (missing) combinations to achieve a full 2-way coverage are meaningful to vendors.

Case Study

- We use differential testing and golden model testing in tandem to identify incorrect behavior in the context of multiple AES implementations tested together.
- We test the following AES implementations on macOS 10.12.5 to determine whether they comply with the specifications and requirements in the standard:
  - OpenSSL 1.0.2k (26 Jan 2017),
  - LibreSSL 2.5.3,
  - Crypto++ 5.6.5,
  - PyCrypto 2.6.1.

Differential Testing

- A Python script uses CCM to generate the missing combinations (AES keys) for a test suite and constructs a list of tuples of the following form from the test suite:

  [(missing key from test suite, IV in test suite, plaintext or ciphertext in test suite)].

- All clients are executed against each tuple to generate a .csv file in which each line is of the following form:

  message, key, iv, openssl, libressl, pycrypto, cryptopp, same_output.

- message stands for either a plaintext or a ciphertext in the corresponding test suite.
- key stands for a missing key.
- iv stands for an Initialization Vector in the test suite.
- Each of openssl, libressl, pycrypto, cryptopp stands for the output (ciphertext or plaintext) of the corresponding library.
- same_output stands for a boolean variable which is true if and only if all libraries generate the same output.

Golden Model Testing

- We use the Cryptographic Algorithm Validation System (CAVS) as a test oracle.

- A script constructs a list of tuples of the following form from a CAVP test suite:

  [(key in test suite, IV in test suite, plaintext or ciphertext in test suite)].

- The script executes all clients against each tuple and generates a .csv file in which each line is of the following form:

  message, key, iv, openssl, libressl, pycrypto, cryptopp.

- message stands for either a plaintext or a ciphertext in the corresponding test suite.
- key stands for a key in the test suite.
- iv stands for an Initialization Vector in the test suite.
- Each of openssl, libressl, pycrypto, cryptopp stands for a boolean variable which is true if and only if the library generates the output (ciphertext or plaintext) in the test suite.

Testing Results

- We conducted differential testing using more than 2,000,000 tuples, finding no discrepancies between the AES implementations.

- Golden model testing using more than 25,000 tuples did not reveal any problems.

Conclusions

- We measured the combinatorial coverage of test vectors provided by the NIST Cryptographic Algorithm Validation Program (CAVP).
- Input models were defined and test vectors measured and analyzed for 2-way, 3-way, and 4-way combinatorial coverage.
- The results of our measurement show that some test vectors do not achieve a full 2-way to 4-way combinatorial coverage, so we generated the missing combinations for these vectors and extended the test suites to achieve a full 2-way coverage.

- We also conducted differential testing on popular AES implementations, such as OpenSSL (v. 1.0.2k 26 Jan 2017), LibreSSL (v. 2.5.3), Crypto++ (v. 5.6.5), PyCrypto (v. 2.6.1), using the extended test suites. Our differential testing of AES implementations on these test suites showed no discrepancies between the implementations.

- Finally, we use the NIST Cryptographic Algorithm Validation System (CAVS) as a golden system against which the AES implementations are tested. Our testing did not reveal any problems.

Questions - Comments

Thank you for your attention!