Cryptanalysis of an MPEG-video Encryption Scheme Based on Secret Huffman Tables

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Abstract—This paper studies the security of a recently-proposed MPEG-video encryption scheme based on secret Huffman tables. Our cryptanalysis shows that: 1) the key space of the encryption scheme is not sufficiently large against divide-and-conquer (DAC) attack and known-plaintext attack; 2) it is possible to decrypt a cipher-video with a partially-known key, thus dramatically reducing the complexity of the DAC brute-force attack in some cases; 3) its security against the chosen-plaintext attack is very weak. Some experimental results are included to support the cryptanalytic results with a brief discussion on how to improve this MPEG-video encryption scheme.

Keywords: MPEG video; data encryption; cryptanalysis; Huffman table; ciphertext-only attack; known-plaintext attack; chosen-plaintext attack; divide-and-conquer (DAC) attack; brute-force attack; partial-key attack

I. INTRODUCTION

The extensive use of digital images and videos in today’s digital world makes the security and privacy issues more and more important. To fulfill such an increasing demand, various encryption algorithms have been proposed in recent years as possible solutions to content protection of digital images and videos [1]–[11], among which MPEG videos attract special attention due to its prominent prevalence in consumer electronic markets [12]–[14]. As an important way of designing MPEG-video encryption schemes, secret Huffman tables have been suggested in some designs [3], [8], [15]–[19].

The MPEG-video encryption scheme proposed in [15] (i.e., Algorithm 1 in [3]) is a light-weight scheme, which encrypts the plain-video by shuffling VLC (variable-length coding) entries of same size in each Huffman table. However, because the bit length of each VLC codeword does not change, the position of each VLC codeword in the video stream does not change either. Thus, an attacker can uniquely locate (and thus determine) all VLC codewords contained in the cipher-video stream, if the plain-video stream or an independent part (such as a picture or a slice) is known. Once all distinct VLC codewords are obtained, the whole secret Huffman table is uniquely reconstructed and the encryption scheme is broken. That is, this light-weight scheme is not secure against known/chosen-plaintext attacks. In addition, as pointed out in [3], the key space of this encryption scheme is very limited (especially for Huffman tables with a small number of VLC entries), so even a brute-force attack may become feasible.

The MPEG-video encryption scheme proposed in [16] can be considered as an enhanced version of that in [15]. In this scheme, five different Huffman tables are shuffled separately and the shuffling operations are generalized to work on VLC entries with different sizes, in the hope that the key space can be enlarged and the security against plaintext attacks can be improved. Furthermore, as a second guard on the security, random bit flipping operations are also introduced to further encrypt each secret Huffman table.

In [8], [17]–[19], multiple Huffman tables (MHT) are introduced, from which one table is secretly chosen for the encryption of each VLC codeword. A so-called “Huffman tree mutation process” is also proposed in [8], [17], [18] to derive more candidate Huffman tables from several original tables.

This paper mainly focuses on security problems with the MPEG-video encryption scheme proposed in [16]. Our cryptanalysis shows that this scheme is not sufficiently secure against DAC (divide-and-conquer) ciphertext-only attack, partial-key attack and known-plaintext attack, and very weak against chosen-plaintext attack.

The rest of this paper is organized as follows. In the next section, a brief introduction to the MPEG-video encryption scheme under study is given. Then, the main cryptanalysis results are presented in detail in Sect. III with some experimental results. Finally Section IV gives a discussion on how to improve the security of the MPEG-video encryption scheme, and the last section concludes this paper.
II. MPEG-VIDEO ENCRYPTION SCHEME UNDER STUDY

Given an uncompressed video as the input, an MPEG encoder compresses the video stream frame by frame in the following steps [12], [13]:

1) (optional, for interlaced MPEG-2 videos only) separate a frame into two field-pictures: a top field and a bottom field;
2) employ differential encoding and motion compensation techniques to remove most redundancy existing between adjacent pictures;
3) divide the current picture into a number of slices, each of which is composed of one or more 16 \times 16 macroblocks;
4) decompose each macroblock into 6, 8 or 12 blocks of size 8 \times 8: 4 luminance blocks; 1, 2 or 4 Cb chrominance blocks; 1, 2 or 4 Cr chrominance blocks;
5) perform DCT (discrete cosine transform) for each 8 \times 8 block, and then quantize the 64 DCT coefficients with a quantiser matrix;
6) transform the 8 \times 8 block into a 1-D vector in one of two possible zigzag scanning orders, and then represent all 64 quantized DCT coefficients (except DC coefficients in intra-blocks) with a number of RLE (run-length encoding) pairs;
7) encode most DCT coefficients (i.e., RLE pairs) and all motion vectors using VLC (variable-length-coding) codewords under the control of some Huffman tables, and represent other DCT coefficients with fix-length bits strings.

A Huffman table is a two-column tale for realizing the Huffman coding algorithm [20], [21], which is an entropy encoding algorithm and transforms an input value into a VLC-codeword with the following rule: the more frequently the input value occurs, the shorter the corresponding VLC-codeword should be, and vice versa. In such a way, one can compress the input data in a lossless form. There are in total 15 Huffman tables used in MPEG-2 standards [13] (less tables are used in MPEG-1 standard [12]), among which ten tables are used to encode data elements in various headers and the following five tables are used to encode visual information – DCT coefficients in each block and motion vectors in each macroblock:

- Table B-10: for encoding motion vectors;
- Table B-12: for encoding the bit size of the differential values of DC coefficients in intra luminance blocks;
- Table B-13: for encoding the bit size of the differential values of DC coefficients in intra chrominance blocks;
- Table B-14: for encoding all DCT coefficients of non-intra blocks and AC coefficients of intra blocks with intra_vlc_format=0, where intra_vlc_format is a picture-specific flag defined in MPEG-2 standard (which is always set to be 0 for MPEG-1 videos);
- Table B-15 (not used in MPEG-1 standard): for encoding all AC coefficients of intra blocks with intra_vlc_format=1.

As an example of the Huffman tables, Table I shows Table B-12 used in MPEG-2 standard.

| Variable length code | dct_vlc_size_luminance |
|----------------------|------------------------|
| 100                  | 0                      |
| 00                   | 1                      |
| 01                   | 2                      |
| 10                   | 3                      |
| 110                  | 4                      |
| 1110                 | 5                      |
| 11110                | 6                      |
| 111110               | 7                      |
| 1111110              | 8                      |
| 11111110             | 9                      |
| 111111110            | 10                     |
| 1111111110           | 11                     |

The encryption scheme proposed in [16] is designed by encrypting the original Huffman tables, i.e., using different (secret) Huffman tables to replace the original ones. The aforementioned five Huffman tables, B-10, B-12, B-13, B-14 and B-15, are chosen to be encrypted separately. These secret Huffman tables are derived from the original ones by combining the following two encryption operations:

- **Shuffling VLC-codewords**: grouping all VLC-codewords into several subsets according to their bit lengths, and then randomly shuffling these VLC-codewords within each subset.
- **Random bit flipping**: randomly flipping the last bit of each VLC-codeword, and adjusting (if needed) other VLC-codewords to keep the prefix rule valid.

After encrypting all the five Huffman tables with both of the above two methods, the bit length of some VLC-codewords should be slightly changed to enhance the security against plaintext attacks (as discussed in Sect. I of this paper) but should not be changed too much, to avoid a large influence on compression efficiency.

In [16], the key space was estimated by enumerating all “good” encryption methods of the shuffling operation and the random bit flipping operation, as shown in Table II. Then, the key space size was calculated to be the product of the five numbers given in the table:

\[(3!)(7! \times 2^{8}) \times (6! \times 2^{8}) \times (6!)(16!) \approx 5.37 \times 10^{27} \approx 2^{92}.\]


1To keep the description simpler, here we mainly consider MPEG-1/2 encoder. For special features of MPEG-4 encoder with respect to MPEG-1/2, see [14] for more details.

2An encryption method is “good” if it can produce unintelligible images. Note that the number of “good” encryption methods may be larger if a looser definition of “unintelligible images” is used.
TABLE II
The number of good encryption methods of each Huffman table (Table 3.6 of [16]).

| Huffman table | Number of good encryption methods |
|---------------|----------------------------------|
| B-10          | 3!                               |
| B-12          | 7! × 2^6                        |
| B-13          | 6! × 2^6                        |
| B-14          | 6!                              |
| B-15          | 10!                             |

As a result of the large key space, it was claimed that the scheme is sufficiently secure. In the next section, we will point out that this claim is not grounded.

In [16], an additional measure is also suggested to further enhance the security against plaintext attacks – reshuffling the Huffman tables after a certain number of frames. In the following, we will mainly consider the basic scheme without the reshuffling mechanism. The effect of the reshuffling mechanism will be discussed later in Sect. IV.

III. CRYPTANALYSIS

In this section, we re-study the security of the aforementioned MPEG-video encryption scheme based on secret Huffman tables, and point out that it is not so secure as claimed in [16], especially against the chosen-plaintext attack. In this section, the terms and notations in MPEG-2 standard [13] will be used, except those existing in MPEG-1 videos only. The following terms are used throughout this section to facilitate the description: 1) the term “picture” is used instead of “frame”, since the encryption scheme is independent of the syntax differences between a picture and a frame; 2) macroblock is abbreviated as “MB”; 3) a self-defined term “MB header” is used to denote the set of all data elements occurring before the first encoded block in an MB (if none of the blocks is coded, the MB header is the MB itself).

A. Ciphertext-only attack

The ciphertext-only attack is the most common attack in practice, since in general the communication channels are open to the public, which means that an attacker can observe a number of ciphertexts and use them to break an encryption scheme [22], [23]. There are two different goals in a ciphertext-only attack: recovering the plaintexts and recovering the secret key. The latter means that the encryption scheme can be completely broken. This paper mainly focuses on the recovery of the secret key, i.e., the secret Huffman tables in the MPEG-video encryption scheme under study.

The simplest ciphertext-only attack is to exhaustively search all possible keys to find the unique correct one, which is called the brute-force attack [22], [23]. Here, a criterion is needed to verify each searched key. For the MPEG-video encryption scheme under study, the occurrence of syntax errors can serve as such a criterion for detecting wrong keys (i.e., wrongly guessed Huffman tables). When a wrong Huffman table is used to decrypt a cipher-video, syntax errors may occur in the decoding procedure due to (but not limited to) the following reasons.

- As mentioned in Sect. I of this paper, to ensure the security against plaintext attacks, there are at least two different bit lengths in a Huffman table. However, once the bit length of a data element (i.e., the bit length of the corresponding VLC-codeword) is wrong, all the following data elements in the current slice cannot be correctly decoded. For example, if \( \text{det}_\text{dc}_\text{size} \) is not decoded correctly in an intra-block, all the following data elements in the current slice cannot be correctly located and decoded.
- For each Huffman table, not all VLC-codewords are valid. For example, in Table B-10, all VLC-codewords have less than 7 zero bits and the prefix “0000 0010” never occurs.
- There always exist 23 continuous zero bits between two adjacent MBs.
- There may exist some marker bits (must be “1”) in the bit stream:
  - (not valid for MPEG-1 videos) when concealment\_motion\_vectors = 1 in an intra-block, there exists a marker bit in the MB header;
  - (for MPEG-1 videos only) in D-picture, the last bit of each MB must be a marker bit named end\_of\_macroblock.
- There exist some constraints on the decoded data elements:
  - each decoded DCT coefficient should not be out of the range \([-2048, +2047]\) after quantization;
  - each decoded motion vector should not be out of the range defined in Table 7-8 of the MPEG-2 standard [13], and must be within the reference picture after adding the coordinates of the predicted MB.
- There must be an EOB VLC-codeword at the end of each block, before which the total number of decoded DCT coefficients must not be greater than 64.
- The number of MBs within each picture should not be greater than a maximal value.
- Some slice headers may be skipped when the video is decoded with wrong Huffman tables, which is forbidden for most videos (for example, the MPEG-1 video and the MPEG-2 video with a restricted slice structure).
By detecting the above syntax errors occurring in the decoding procedure, one can distinguish most wrong Huffman tables. In addition, there generally exist a lot of information redundancies in each decoded block, MB, slice, picture and between adjacent blocks, MBs, pictures and frames. Therefore, even when no syntax error is detected, one can still distinguish the wrong Huffman table if a meaningless picture or a number of slices are decoded or if there exists excessive noise between many adjacent blocks.

Now, let us see how frequently these syntax errors occur. To make things simpler, denote the average probability of occurrence of a syntax error at each syntax element by \( p \). Then, for a picture with \( L \) syntax elements, the probability that at least one syntax error occurs within this picture will be \( P(L) = 1 - (1 - p)^L \). For an MPEG-1 video of size \( M \times N \), the number of syntax elements is about \( 6MN\lambda \), where \( \lambda \) is a factor determined by the average number of syntax elements in each block and ranges roughly from 1/64 to 1. As an example, taking \( M = 176 \), \( N = 144 \), \( \lambda = 1/64 \) and \( p = 0.001 \), one can easily calculate and obtain \( L = 2376 \) and \( P(L) \approx 0.9072 \). Since the value of \( \lambda \) is generally larger than 1/64 and the value of \( p \) might not be so small, it is generally a high-probability event to observe at least one syntax error within one MPEG-picture. Note that in reality the values of \( p \) and \( \lambda \) vary in a wide range due to the following reasons: 1) there are a lot of possibilities of encoding a video within the framework of MPEG standards; 2) there are some optional data elements in MPEG standards; 3) the occurrence of some kinds of syntax elements depends on the contents of the encoded blocks or other syntax elements; 4) different blocks correspond to different distributions of DCT coefficients, which directly influence the values of \( \lambda \) and \( p \); 5) different Huffman tables (especially these short VLC-entries) correspond to different value of \( p \). Therefore, instead of estimating the values of \( p \) and \( L \), the efficiency of the syntax-error detection process will be shown by carrying out experiments on some sample videos.

Because the five Huffman tables are used for different parts of the whole video bit-stream, it is possible to separately guess them one by one. This means that one can use the so-called divide-and-conquer (DAC) attack [22], [23] to break the MPEG-video encryption scheme. In other words, the key space of the encryption scheme will be the \textit{sum}, not the \textit{product}, of the sub-spaces of the five tables. Next, let us see how to separately break the five Huffman tables by detecting syntax errors in the video decoding procedure.

1) Reconstructing Table B-10: Following the MPEG-2 standard, Tables B-12/13/14/15 are all independent of the decoding of the first MB header in a slice, which makes the separate reconstruction of Table B-10 possible. When a wrong Table B-10 is used, the following syntax errors may occur when the first MB header of a slice is decoded.

- Some decoded motion vectors may be invalid, especially for those MBs near the picture edge.
- When \textit{concealment motion vectors} = 1 in an intra-block, the marker bit in the MB will be wrong (i.e., equal to 0) with a probability of 0.5 (under the assumption that each bit in the video stream is distributed uniformly).
- When \textit{macroblock pattern} = 1, “0000 0000 0” never occurs in \textit{coded block pattern} encoded by Table B-9.

Note that in each slice only the first MB header can be used to detect syntax errors about Table B-10, so the average number of involved syntax elements in each block (i.e., the value of \( \lambda \) corresponding to this table) may be too small, especially for pictures with a small number of slices and/or slow motion. When such an event happens, one has to exhaustively search through Table B-10 and other Huffman tables. Experiments showed that this event really happened for many MPEG videos.

2) Reconstructing Table B-14: Since all DCT coefficients in a non-intra MB are encoded with Table B-14, syntax errors may occur when continuous non-intra MBs in a slice are decoded with a wrong Table B-14. Because most MBs in a P/B-picture are non-intra MBs, the occurrence probability of syntax errors (i.e., the value of \( p \) corresponding to this table) will be relatively high.

To test how frequently syntax errors of this kind occur in real attacks, we observed the decoding process by exchanging the following two VLC-entries in Table B-14 – “11s” and “011s”, which represent RLE-codewords (0,1) and (1,1), respectively. For a large number of test MPEG-1/2 videos, syntax errors started to occur after a few number of MBs were decoded. See Fig. for the decoding results of an MPEG-1 video “Carphone” (of size 176 × 144) and an MPEG-2 video “Tennis” (of size 704 × 576). If the whole Huffman table is heavily shuffled, syntax errors will occur even more frequently.

3) Reconstructing Table B-12: Once Table B-14 is reconstructed, Table B-12 can be further exhaustively searched in intra MBs with \textit{intravlc format} = 0. If the attacker can get at least one MPEG-1 cipher-video, Table B-12 can always be broken separately (Table B-15 is not used in MPEG-1 videos, which means \textit{intravlc format} = 0). If all intra MBs in all known plain-videos are encoded with \textit{intravlc format} = 1, Table B-12 has to be exhaustively searched together with Table B-15 (see below), which is generally a rare event when an attacker can collect a number of cipher-pictures to carry the ciphertext-only attack.

In the case that only two VLC-codewords, “00” and “01”, in Table B-12 were swapped, we tested the decoding results of some MPEG-1/2 videos. Figure gives the results

4All other MBs cannot be located without knowing Tables B-12/13/14/15.

5The two VLC-codewords were chosen due to their frequent occurrence in the MPEG-1/2 video stream.

6The 1st picture of “Tennis” is encoded with \textit{intravlc format} = 1, while the 2nd picture with \textit{intravlc format} = 0.
of the MPEG-1 video “Carphone” and the MPEG-2 video “Tennis”. One can see that the syntax errors still occur very frequently. Note that the swapped VLC-codewords have the same bit length, so a stronger shuffling of Table B-12 shall cause much more syntax errors.

4) Reconstructing Table B-15: If Table B-12 has been successfully guessed, Table B-15 can be exhaustively searched in luminance blocks of intra MBs with $\text{intravlcformat} = 1$, just like the case of reconstructing Table B-14. If Table B-12 cannot be separately broken, Tables B-12 and B-15 have to be exhaustively searched together.

By swapping “10s” and “010s”, which represent (0,1) and (1,1), respectively, in Table B-15, we tested the decoding results of some MPEG-2 videos (note that this table is not used in the MPEG-1 standard). Figure 3 gives the results of the MPEG-2 video “Tennis”. It can be seen again that many syntax errors still occur.

5) Reconstructing Table B-13: After Tables B-12, 14 and 15 are broken, Table B-13 can be exhaustively searched in chrominance blocks of intra MBs. If there are intra MBs with $\text{intravlcformat} = 0$, Table B-13 can be exhaustively broken immediately after Table B-14 is broken, without knowing Table B-15.

By exchanging two VLC-codewords, “01” and “10”, in Table B-13, we tested the decoding results of some MPEG-1/2 videos. The results corresponding to the MPEG-1 video “Carphone” and the MPEG-2 video “Tennis” are shown in Fig. 4. Again, many syntax errors can be observed. Due to a similar reason in the case of Table B-12, even more syntax errors are expected in a real shuffling of Table B-13.

Finally, based on the above analysis and experimental results, let us estimate the complexity of the above DAC attack under four different conditions as follows:

- **when Table B-10 is separately reconstructed:**
  - when Table B-12 is separately searched: $(3!)^2 + (7! \times 2^6) + (6! \times 2^8) + (6!) + (16!) \approx 2^{44.3};$
  - when Table B-12 is searched together with Table B-15: $(3!)^2 + (7! \times 2^6) \times (16!) + (6! \times 2^8) + (6!) \approx 2^{42.5};$
- **when Table B-10 is not separately reconstructed:**
  - when Table B-12 is separately searched: $(3!) \times (7! \times 2^6) + (6! \times 2^8) + (6!) + (16!) \approx 2^{46.8};$
  - when Table B-12 is searched together with Table B-15: $(3!) \times (7! \times 2^6) + (6! \times 2^8) \times (16!) + (6! \times 2^8) + (6!) \approx 2^{46.8};$
For example, if the "Escape" entry in Table B-14 or B-15 is not reconstructed, one can still use the partially-recovered Huffman table itself, where the word “practicable” means that a partially-reconstructed Huffman table can be used to decrypt some specific target ciphertexts, though not all possible ciphertexts.

Furthermore, Table B-15 is a very special Huffman table, since it never occurs in MPEG-1 videos and may not occur in some MPEG-2 videos as well. So, Table B-15 can be simply neglected when breaking such videos, which means that Table B-12 can always be searched separately. In this case, the key space under the DAC ciphertext-only attack becomes even smaller:

- when Table B-10 is separately reconstructed: $(3!) + (7! \times 2^6) + (6! \times 2^8) + (6!)$ \(\approx 2^{19.0}\);
- when Table B-10 is not separately reconstructed: $(3!) \times ((7! \times 2^6) + (6! \times 2^8) + (6!)) \approx 2^{21.5}$.

One can see that the key space is so small that it is even possible to find the secret Huffman tables within seconds on a PC with a 1GHz CPU (note that $1G = 2^{30} \gg 2^{21.5}$).

C. Chosen-plaintext attack

The chosen-plaintext attack is a very strong attack, in which one can (intentionally) choose some plaintexts and observe the corresponding ciphertexts to break an encryption scheme [22], [23]. With the help of some chosen plaintexts and ciphertexts, it is possible to directly determine the secret Huffman tables without exhaustively guessing them in all possible candidates. In the following, we show how to choose the data elements in a plain-video to carry out a successful chosen-plaintext attack.

1) Reconstructing Table B-10: Choose a P/B-picture so that all MBs are encoded as “Not Coded”, i.e., only MB headers occur in this picture and all blocks are skipped. Given any two MBs in a slice, one can easily locate the 23 zero bits between the two MBs and all data elements occurring before motion vectors in the first MB header. Note that the data elements in the second MB header can be intentionally chosen to facilitate such a locating procedure. Then, one can extract a bit segment from the first MB header, which is composed of two or four motion vectors. In the extracted bit segment, the values of motion_residues, drm_vectors and the sign bits of the motion vectors can be chosen to uniquely distinguish each motion_code, i.e., each VLC-codeword encoded with the secret Table B-10. If necessary, $f_{\text{code}}[r][s]$ can also be intentionally chosen to help the extraction of the VLC-encoded motion_codes. By choosing the values of 17 consecutive motion_codes to be 0, ..., 16, respectively, all entries in Table B-10 can be uniquely determined. Apparently, to completely break Table B-10, only a few MBs (not a full picture) are needed.

B. Partial-key attack

There exists another serious defect in the MPEG-video encryption scheme under study: with a partially-recovered key (i.e., partial entries of the Huffman tables), it is still possible to decrypt a cipher-video, if this cipher-video does not contain any undetermined entries in the Huffman tables. For example, if the "Escape" entry in Table B-14 or B-15 is not reconstructed, one can still use the partially-reconstructed Huffman tables to decrypt a cipher-video that contains a large number of VLC data elements, syntax errors and residuals, dm_vectors and the sign bits of the motion vectors can be separately broken in most cases, where note that Table B-12 can always be searched separately. In this case, the key space under the DAC ciphertext-only attack becomes even smaller:

One can see that in all cases the complexity will be much smaller than the one given in [16]: $(3!) \times (7! \times 2^6) \times (6! \times 2^8) \times (6! \times 16!) \approx 2^{92}$. Considering that Table B-12 can always be searched separately. In this case, the key space under the DAC ciphertext-only attack becomes even smaller:

- when Table B-10 is separately reconstructed: $(3!) + (7! \times 2^6) + (6! \times 2^8) + (6!) \approx 2^{19.0}$;
- when Table B-10 is not separately reconstructed: $(3!) \times ((7! \times 2^6) + (6! \times 2^8) + (6!)) \approx 2^{21.5}$.

Fig. 4. The decoded results of the MPEG-1 video “Carphone” and the MPEG-2 video “Tennis”, when only two VLC-codewords were exchanged in Table B-13: a) the 1st picture of “Carphone”; b) the decoded 1st picture of “Carphone”; c) the 1st picture of “Tennis”; d) the decoded 1st picture of “Tennis”.

B-15: $(3!) \times ((7! \times 2^6) \times (6! \times 2^8) + (6!)) \approx 2^{91.8}$. One can see that the key space is so small that it is even possible to find the secret Huffman tables within seconds on a PC with a 1GHz CPU (note that $1G = 2^{30} \gg 2^{21.5}$).
2) Reconstructing Table B-14: After reconstructing Table B-10, one can continue to break Table B-14 in non-intra MBs. The entries in Table B-14 can be reconstructed as follows:

- **EOB and Escape entries:** At the beginning of the first MB in a slice, choose the following two plain-blocks (in the zigzag scanning order, the same hereinafter): block \#1 = \(0, 0, 0, \ldots, 0, \text{level}_e, 0, \ldots\), block \#2 = \(0, 0, 0, \ldots, 0, -\text{level}_e, 0, \ldots\), where \((\text{run}_e, \text{level}_e)\) forms an Escape RLE-codeword (i.e., not a valid entry in Table B-14). Then, the video bitstream corresponding to the two plain-blocks will be: “Escape, run, level, EOB, Escape, run, -level, EOB”. By choosing \(\text{run}_e, \text{level}_e\) to be some special values and locating the two fixed-length bit strings: “\(\text{run}_e, \text{level}_e\)” and “\(\text{run}_e, -\text{level}_e\)”, it is easy to determine the Escape and EOB VLC-codewords of Table B-14.

- **Other entries:** Choose a block with two RLE-codewords: “\(0, \ldots, 0, \text{level}, 0, \ldots, 0, \text{level}_e, 0, \ldots\)” \((\text{run}, \text{level})\) is a valid entry in Table B-14 and \((\text{run}, \text{level})\) is an Escape RLE-codeword. By choosing \((\text{run}, \text{level})\) properly, one can easily extract the VLC-codeword of \((\text{run}, \text{level})\) from the bit stream. Repeating this process for all RLE-codewords in Table B-14, one can completely recover the whole Table B-14.

In the above reconstruction process, the number of required blocks is equal to the number of entries in Table B-14, which means only tens of MBs.

3) Reconstructing Tables B-12 and B-13: Since AC coefficients of intra-blocks are encoded in a similar way to the motion vectors, the method of reconstructing Table B-10 can also be used to break Tables B-12 and B-13. To break the entry corresponding to \(\text{dct}\_\text{size} = s\), choose an intra-block as follows: “\(\text{level}, 0, \ldots, 0\)”, where \text{level} has \(s\) significant bits. Then, the video bitstream corresponding to this block will be “\(\text{dct}\_\text{size}, \text{dct}\_\text{differential}, \text{EOB}\)”. Since EOB and \text{dct}\_\text{differential} are both known, it is easy to determine the VLC-encoded \text{dct}\_\text{size}. Given 12 luminance blocks with \(s = 0 \sim 11\), Table B-12 can be completely reconstructed. Similarly, given 12 chrominance blocks with \(s = 0 \sim 11\), Table B-13 can be completely reconstructed. Apparently, the number of required chosen MBs is 3, 6 or 12 according to the value of \text{chroma}\_\text{format} (4, 2 or 1).

4) Reconstructing Table B-15: After reconstructing Tables B-12 and B-13, one can break Table B-15 by choosing some intra-blocks, in the same way of reconstructing Table B-14.

As a whole, one can see that only tens of chosen MBs are enough to break all the five secret Huffman tables. When the picture is not too small, this means that only one chosen picture is enough to break the whole encryption scheme. So the MPEG-video encryption scheme is very weak against chosen-plaintext attack.

D. Known-plaintext attack

The known-plaintext attack is a weak version of chosen-plaintext attack, in which one can only passively observe a number of plaintexts and the corresponding ciphertexts to break an encryption scheme [22], [23].

Apparently, if some chosen blocks mentioned in the above-mentioned chosen-plaintext attack are observed in a known-plaintext attack, the corresponding entries in the involved Huffman tables can be immediately reconstructed. In addition, the FLC (fixed-length coding) data element following \text{dct}\_\text{size} can be used in known-plaintext attack to uniquely locate \text{dct}\_\text{size}. This means that Tables B-12 and B-13 may be reconstructed directly. Also, the reconstructed VLC-entries in a Huffman table can be used to locate other undetermined VLC-entries and to detect wrong candidate entries, which can further reduce the attack complexity. Generally speaking, the complexity of the known-plaintext attack shall be much smaller than the complexity of the DAC brute-force attack, though more plain-MBs are required as compared with chosen-plaintext attack.

IV. IMPROVING THE MPEG-VIDEO ENCRYPTION SCHEME

Though the main focus of this cryptanalysis paper is to point out some security flaws of the MPEG video encryption scheme proposed in [16], in this section we give a brief discussion on how to improve the security of the MPEG video encryption scheme under study, hoping that more sequential studies in this research area can be motivated.

To improve the security of the MPEG-video encryption scheme, a simple way is to change the Huffman tables frequently. In [16], it was suggested to reshuffle the Huffman tables after certain number of frames. Generally speaking, these reshuffling operations might be enough to provide an acceptable resistance against ciphertext-only attack. However, even reshuffling these Huffman tables frame by frame is generally not sufficient for the security against the above chosen-plaintext attack, since a few number of slices may be enough to break the secret Huffman tables. From the most conservative point of view, one has to reshuffle the Huffman tables for each VLC-codeword. Such a heavy reshuffling process will dramatically reduce the speed of the whole system and become impractical in many real applications.

Another possible solution is to use multiple Huffman tables as suggested in [8], [17]–[19]. As a typical implementation of this kind of MHT-encryption schemes, a stream cipher (or a secure PRNG) is adopted to determine the secret Huffman table from multiple candidate tables for each VLC-codeword. However, as is well known in cryptology, a stream
cipher is not secure against plaintext attacks if the key is reused to encrypt more than two plain messages. Thus, in real applications, to further guarantee the security of this MHT-encryption scheme against plaintext attacks, one of the following practical measures may be adopted to avoid potential security defects that may arise from the embedded stream cipher.

- Avoiding reuse of the same secret key to encrypt two videos, i.e., changing the secret key for different videos: this measure has to be used together with a key management system and may not be very useful in low-cost video applications (such as storage of private videos in personal computers and mobile devices).
- Assigning a unique ID (UID) for each video (by the manufacturer or by the end user), and then using the UID to initialize the stream cipher together with the secret key: this measure can be considered as a special case of the above measure, but it can work without a key management system.
- Using plaintext or ciphertext feedback to make the stream cipher dependent on the whole plain-video: this measure will bring up an error-propagation problem, but can work well in error-free environments.
- Combining the secret selection of the Huffman tables with a block cipher to construct a product cipher: the block cipher should be sufficiently simple and fast, and can even be insecure when used separately (for example, with a small block size). This measure may lead to some new designs of MPEG video encryption schemes and needs future studies.

Finally, note that the security defects about the DAC brute-force attack and the partial-key attack cannot be essentially avoided even with the above countermeasures, since they are actually caused by the inherent feature of an MPEG-video’s syntax structure. This implies that only using secret Huffman tables is not sufficient to provide an acceptable security level for all MPEG-videos. Some more powerful techniques, such as secret permutation of DCT coefficients and encryption of VLC indices [9]–[11], have to be introduced to achieve such a goal for MPEG-video encryption. In future, we will investigate how to combine different encryption methods to design MPEG-video encryption scheme with high level of security.

V. CONCLUSIONS

This paper has analyzed the security of a recently-proposed MPEG-video encryption scheme, which bases its security of the use of some secret Huffman tables. As a result, it is found that the scheme is not sufficiently secure against DAC (divide-and-conquer) brute-force attack and known-plaintext attack, and is very weak against the chosen-plaintext attack. Another serious security defect of this scheme is that a partially-known key may be used to decrypt some cipher-videos, which further causes a reduction of the key space. Based on our cryptanalytic results, a brief discussion is also given on how to further improve the security of the MPEG-video encryption scheme under study.

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