Embedded Blockchains: A Synthesis of Blockchains, Spread Spectrum Watermarking, Perceptual Hashing & Digital Signatures

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Abstract
In this paper we introduce a scheme for detecting manipulated audio and video. The scheme is a synthesis of blockchains, encrypted spread spectrum watermarks, perceptual hashing and digital signatures, which we call an Embedded Blockchain. Within this scheme, we use the blockchain for its data structure of a cryptographically linked list, cryptographic hashing for absolute comparisons, perceptual hashing for flexible comparisons, digital signatures for proof of ownership, and encrypted spread spectrum watermarking to embed the blockchain into the background noise of the media. So each media recording has its own unique blockchain, with each block holding information describing the media segment. The problem of verifying the integrity of the media is recast to traversing the blockchain, block–by–block, and segment–by–segment of the media. If any chain is broken, the difference in the computed and extracted perceptual hash is used to estimate the level of manipulation.

Index Terms – blockchains, digital watermarking, perceptual hashing, digital signatures, tamper detection, deepfakes.

1 Introduction
The proliferation of artificially–generated video and audio has become more prevalent in recent years with advances in deep learning technologies including generative adversarial networks (GANs) and are now at a point where they are staggering realistic [30][20]. These are commonly known as deepfakes.

The majority of the methods proposed to detect deepfakes involve using deep learning [15]. These deep learning methods are improving rapidly; in the future it may be impossible to distinguish deepfakes from real media.

There is an ever increasing commercial desire to track the provenance and integrity of audio, photos and video. Ongoing notable projects aiming to address deepfakes or manipulated video and audio include The Deepfake Detection Challenge by Facebook and Microsoft, The News Provenance Project by The New York Times and the DARPA MediFor (Media Forensics) program [9][17][21].

Contemporary solutions for detecting deepfakes or manipulated media generally operate after the suspected manipulations have taken place. We propose a two–step process; firstly, the media is marked in real time as its captured with a series of unique identifiers. Subsequently if the provenance of the media is questioned, the second step of verification of the media occurs.

In order to verify the integrity of the media using only the media and its embedded data, the unique identifiers should possess the following properties:

1. Hidden from human perception.
2. Provide proof of ownership.
3. Describe the content.
4. Impose a temporal ordering on the content.

These identifiers could be hidden (or partially hidden) from human perception using a spread spectrum watermark [7][8][22][26].

Proof of ownership can be verified by extraction of the encrypted watermark data, or by verification of a digital signature once the watermark data is extracted and decrypted.
Cryptographic hashing can provide a bit-level description of the content, and perceptual hashing could provide a flexible description of the content.

Blockchains are used to link segments of the media together and impose a temporal ordering via hashing. The blockchain also prevents the removal, insertion or rearranging of any segments (blocks) of the media.

We call the synthesis of blockchains, encrypted spread spectrum watermarking and perceptual hashing an Embedded Blockchain.

Our solution does not require a trusted authority to verify the media stream against an original, as all the necessary data describing the media is contained within the Embedded Blockchain which is hidden in the media.

An obvious application for such a scheme is smartphones – where hidden datasets could be embedded in the video and audio; which would provide a unique link to the phone and mark the dataset with information describing its contents.

2 Blockchains

Blockchains were invented in 2008 by a person or group of people, under the name Satoshi Nakamoto [18]. The blockchain serves as a public transaction ledger of the cryptocurrency, Bitcoin. Nakamoto outlined a data structure for chaining blocks of data together by their cryptographic hash. Previously, Haber and Stornetta developed a robust method for time-stamping digital documents by hashing the document with that of the previous document, thus making a cryptographically linked list [13].

The central idea is any changes to the data of any one block will, with overwhelming probability, change the hash of the block and all subsequent blocks; thus imposing an immutable temporal ordering of the data in the blocks.

Figure 1: A conceptual diagram of the blockchain.

Our use of the blockchain is primarily for its data structure. For our purposes we can think of the blockchain as a cryptographically linked list.

3 Spread Spectrum Watermarking

Spread spectrum (Digital) watermarking (or watermarking) is a steganographic technique which embeds an imperceptible message in a noise-tolerant signal [7][8][22][26]. Spread spectrum watermarking was invented by Andrew Tirkel and Charles Osborne in 1992 [26]. Commonly watermarked noise-tolerant signals include audio, imagery and video. More abstract datasets are also amenable to watermarking [23].

The hidden message is embedded into the signal using families of sequences, or multi-dimensional arrays which possess good periodic autocorrelation and pairwise cross-correlation [1][3][27]. The message is encoded as cyclic shifts of the sequences or multi-dimensional arrays.

A secure watermark can be created by encrypting the families watermarking arrays prior to embedding in the signal. In recent years a number of image–based encryption methods have been proposed [5][24][29][31].

The process of embedding a watermark in a media stream is summarised in the following diagram.

Figure 2: A conceptual diagram of the watermark embedding process.

In the diagram above, the watermarking parameters may include the embedding strength, the embedding do-
main, the family of arrays, the array size and dimensionality of the arrays.

The number of arrays required to embed the hidden message depends on the message length, the array size and array dimensionality (as increasing the dimensionality increases the watermark payload capacity [3]). Estimating the optimal embedding strength requires balancing perceptibility of the watermark with robust extraction of the hidden message. Furthermore, the robust extraction of the watermark is dependent on the number of arrays embedded and consequently depends on the size of the hidden message.

The extraction of a watermark is summarised in the following diagram.

![Watermark Extraction Diagram](image)

**Figure 3:** A conceptual diagram of the watermark extraction process.

To determine if the watermark extraction was successful, the signal-to-noise ratio (SNR) of each array is compared to a predetermined noise level.

### 4 Cryptographic & Perceptual Hashing

Cryptographic hash functions compress an arbitrary number of bits into a fixed number of bits. The cryptographic hash is a one-way function, which are computationally prohibitive to invert. They act as a unique identifier of the input data, such that two similar inputs will almost certainly result in vastly different outputs (by the avalanche effect [10]). If two distinct inputs return the same cryptographic hash, known as a collision, then the hashing function is considered broken. Many hashing functions have been broken, such as the widely used MD5 hash [4]. Robust cryptographic hashing functions include the SHA2 family, which was developed by the NSA.

Perceptual hashing functions are very different to cryptographic hashes. Unlike cryptographic hashes, perceptual hashes are similar if their inputs have similar features. The difference between two perceptual hashes is used as a metric of dissimilarity. Perceptual hashes are applicable to both audio and imagery [11][19][28].

### 5 Digital Signatures

Digital signatures are a form of asymmetric encryption which is used to bind a person or entity to digital data. We sign some data with a private key. Once signed, the data and the signature can be disseminated. Verification happens with a public key, the data and the signature. If the data or signature has changed the public key will invalidate the signature.

Incorporating a digital signature into the Embedded Blockchain gives us the ability to distribute the watermark encryption password, so the media can be independently verified and still keep control of the creation of our unique Embedded Blockchain via the private key of the digital signature.

### 6 Embedded Blockchains

We now have all the necessary ingredients to describe the Embedded Blockchain. Our description is in terms of video, however it can be applied to audio or any abstract dataset which has a temporal or lexical ordering and is amenable to spread spectrum watermarking.

As discussed earlier, we embed a series of groups of unique identifiers into the video with the following features:

1. Hidden from human perception.
2. Provide proof of ownership.
3. Describe the content.
4. Impose a temporal ordering on the content.

Each group of unique identifiers describes one segment of the media. We refer to the data in this group as a block. The blocks are chained together using cryptographic and perceptual hashes. Additionally, a small amount of user-defined data may be included in each block, for example, a time stamp or some covert information.

Before we can describe the embedding and extraction processes we need to decide on the segment size that we
wish to describe in each block. For simplicity we can think of the segment size as a single frame of video. This size can vary to accommodate real time embedding or to balance embedding time with the fidelity of the perceptual hash for application-specific requirements.

6.1 Describe & Embed

Consider the first segment, which is different to all subsequent segments, as it does not contain a block. We compute the perceptual and cryptographic hashes of this segment and digitally sign the perceptual hash of the segment. Then we form the block by accumulating this data with the user-defined data and embed it into the second segment using the spread spectrum watermark.

Segments are chained together by embedding the data describing segment \( n \) into segment \( n + 1 \). This is summarised in the diagram below.

![Diagram](image)

Figure 4: A conceptual diagram of the creation of the Embedded Blockchain.

Given a video which contains an Embedded Blockchain we wish to verify that the video has not been manipulated. As this video contains an Embedded Blockchain, we can recast the problem of detecting any manipulations to traversing the Embedded Blockchain, block–by–block and segment–by–segment, where for each segment we compute the cryptographic hashes, perceptual hashes and digital signatures, then compare these computed values to the corresponding data extracted from the embedded block. If the cryptographic hash does not match, then some modification has occurred and we can measure the level of modification with the difference between the computed and extracted perceptual hashes.

6.2 Extract & Verify

If the block is not recoverable from the watermark, then it is immediately evident that the chain of blocks is broken and the segment has been modified.

It is important to note that we have not relied on any external data to make this determination. For example, we have not compared the video to a untampered original, nor looked up the hash of the video in a database, nor relied upon a deep learning approach which needs millions of test cases for training.

The extraction and verification scheme is summarised in the following diagram.
Figure 5: A conceptual diagram of verifying one block.

When extracting the block from the watermark, the same watermarking parameters used in the embedding process must be used.

There is no requirement that the user data is static from block to block, and may be accumulated block–by–block and bit–by–bit to store larger amounts of data.

### 6.3 Practical Considerations

We will now detail some practical considerations for the design and implementation of an Embedded Blockchain. These include

1. **The hash size.** The main consideration with the hash size is the need to balance the security of the cryptographic hash and digital signature, the fidelity of the perceptual hash, and the size of the user data embedded in each block with the size of the hidden message embedded in the watermark.

2. **The segment size.** Increasing the segment size decreases the temporal resolution of each block, however it increases the space to store the block. Increasing the segment size is useful when embedding in a format which aggressively compresses the media. Increasing the segment size also decreases the computational work required to create the Embedded Blockchain.

3. **Comparing perceptual hashes.** Absolute numerical equality would be desirable, however when using lossy compression to store the media often a threshold needs to be estimated (as a function of the media size, the segment size and the bitrate of the perceptual hash).

4. **The size and dimensionality of the watermarking arrays.** Increasing the size of the arrays also increases the SNR of the block extraction. Increasing the dimensionality also increases the size of the hidden message. On the other hand increasing the dimensionality also decreases the bit-rate of each shift.

5. **The embedding domain of the watermark.** Common choices are the spatial and Fourier domains, however there are many possible choices [6][12][25]. The choice of embedding domain will effect the perceptibility and SNR of the watermark extraction.

6. **The user data.** Increasing the size of user data increases the size of the block and subsequently the number of watermarking arrays required to embed, which decreases the SNR of the watermark extraction.

### 6.4 Exemplar Calculation of the Block Size for Compressed Video

A key software engineering challenge of the Embedded Blockchain is the data carrying capacity of the watermark in the presence of lossy video compression schemes, whilst remaining visually imperceptible.

We will now detail a calculation which estimates the data capacity of the watermark for a single segment of 4K resolution video (3840 by 2160 px). We have embedded a family of 2D arrays of size $1087 \times 1087$ in a $2 \times 4$
tiled arrangement. These arrays possess good autocorrelation and pairwise cross-correlation properties [3]. The watermark embedding was in the spatial domain and the segment size (the number of frames described in a single block) was 15, or approximately half-second blocks.

Each 2D watermarking array can hold 2 integers in base 1087. If we allocate 3, 256–bit hashes for the digital signature, perceptual hash, cryptographic hash and 256–bits for user data in each block, then we must store 1024 bits in the watermark (per block). We can bit–pack the 1024 bits into 104 base 1087 integers, or 52, 2D arrays.

In the following graphic we have plotted the mean SNR of the watermark extraction with the size of the hidden message.

![Figure 6](image_url)

Figure 6: A comparison of the watermark extraction SNR with the length of the hidden message. The compression schemes used were MJPEG, MPEG–1, MPEG–2 and H.264. The estimated SNR of random noise and the 3– and 6–sigma confidence intervals are shown.

This calculation indicates a 1024 bit block size is feasible, as the SNR for a message length of 104 is above the 6–sigma confidence interval from the mean noise level. For MJPEG, MPEG–1 and MPEG–2 we achieved this message length with an embedding strength of 0.5%, whereas for H.264 we needed an embedding strength of 1.5%. The required increase in embedding strength is due to the aggressive compression used in the H.264 scheme.

7 Conclusions

We have described a two–step scheme to detect manipulations in media including video and audio. If efficiently implemented, this scheme should be able to run passively on a battery–powered device like a smartphone when capturing a video or audio recording. If so, it is likely that in the future all recording devices will contain an Embedded Blockchain–like scheme for proof of ownership and content verification.

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