Traitor-Proof PDF Watermarking

Fabrizio d’Amore\textsuperscript{1} and Alessandro Serpi\textsuperscript{2}

\textsuperscript{1} Sapienza Univ. di Roma, Dip. Ingegneria informatica, automatica e gestionale A. Ruberti, Italia
https://www.diag.uniroma1.it/en
damored@diag.uniroma1.it
\textsuperscript{2} Independent researcher, Roma, Italia
serpi.1647244@studenti.uniroma1.it

Abstract. This paper presents a traitor-tracing technique based on the watermarking of digital documents (PDF files in particular). The watermarking algorithm uses a chain of three separate techniques that work in synergy. The embedded payload can withstand a wide range of attacks and cannot be removed without invalidating the credibility of the document.

We will present an implementation of the approach and discuss its limitations with respect to documents that can be watermarked and quality of the watermarked documents. We will also analyse two payload alternatives and how the encryption scheme may alleviate the chilling effect on whistle-blowing.

Keywords: Text watermarking, Traitor tracing, Pdf

1 Introduction

All organisations store and process sensitive documents whose unauthorised disclosure would result in a financial and credibility loss for the organisation itself. Given their importance, usually those documents are stored as PDF files and are accessible only by specific vetted users. Therefore, they are quite safe from both external and internal attacks. However, users that are legitimately authorised to access sensitive documents may want to leak them; take for example disgruntled employees in search of revenge or whistle-blowers that failed to start a legal investigation. Thus, organisations need a PDF watermarking algorithm that invisibly embeds a robust payload into sensitive documents to identify the user that downloaded and divulged them. In other words, organisations need a traitor-tracing scheme based on digital watermarks.

There are several approaches to invisible document watermarking, each with its own advantages and vulnerabilities. In this paper, we will present a novel traitor-tracing scheme that implements three different approaches to withstand a wide range of attacks.

We will explain the workflow required to produce a document visually similar to the original and what limitations it causes. We will also analyse two payload alternatives and how to alleviate the chilling effect on whistle-blowing.
1.1 Related Works

There are several approaches to document watermarking. The simplest technique that modifies the document itself is to embed information into the file's metadata. However, it is not robust as the payload is easily erased. We can consider the document as a series of images that can be watermarked with general-purpose techniques or specific for textual documents. The watermark withstands printing, but it is eliminated if the adversary employs OCR or re-types the document.

Font-based algorithms deserve a separate analysis thanks to their heterogeneity. They can be considered as image-based techniques with special properties. [18] was the first to use altered character glyphs to watermark textual documents. They proposed two techniques, one changes the glyphs in specific locations, the other changes all glyphs of specific characters [18]. Only the latter withstands partial document erasure, but its capacity is lower than the former’s. [26] were the first to treat fonts as peculiar drawings and to design a watermarking algorithm that took advantage of their intrinsic characteristics by changing the vector curves [26]. Equivalent techniques have been proposed for non-Latin characters such as Arabic [11] and Chinese [25].

A structural watermarking algorithm alters the formatting in order to embed the payload. [6] were the first to describe algorithms that modify inter-word and inter-line spaces [6, 7]. [13] proposed an algorithm that uses average inter-word space statistics and increased robustness by using word classes [16]. Structural watermarks have the same advantages and drawbacks as image-based ones 

3 In fact, they can be considered as highly specialised image-based watermarking algorithms.

A structural watermarking algorithm alters the formatting in order to embed the payload. [6] were the first to describe algorithms that modify inter-word and inter-line spaces [6, 7]. [13] proposed an algorithm that uses average inter-word space statistics and increased robustness by using word classes [16]. Structural watermarks have the same advantages and drawbacks as image-based ones. The payload withstands printing, but not OCR and re-typing. In addition, if the adversary has the document in the original format, he/she can easily eliminate the payload.

Linguistic watermarking algorithms act directly on the text. [2] were the first to propose semantic and syntactic watermarking schemes [2]. [28] designed syntactic algorithms that encode a payload using substitution of synonyms [28] and abbreviations, acronyms, and typographical errors [27]. [21] analysed several tools for syntactic watermarking [21] and proposed morpho-syntactic editing [22].

2 Preliminaries

Document watermarking techniques can be classified into blind, semi-blind and non-blind schemes based on the information required to extract the payload \( p \) from a watermarked document \( d_w \). Blind algorithms need only the watermarked document (and the secret key \( k \), if present). Non-blind algorithms require in addition the original document \( d \). Semi-blind algorithms are slightly different because they check whether a specific payload was embedded into a watermarked document.
Invisible watermarking assumes an active adversary whose objective is to eliminate the watermark without compromising the document’s integrity. The actions that the adversary can perform are usually divided into content- and formatting-based attacks. In the former category fall all actions that alter the information contained in the document, such as synonym substitution, syntactic transformations, and word insertion, deletion and rearrangement. In the latter category fall all actions that alter the presentation of the document, such as font modification, printing, OCR, retyping, and rotation.

Since Linguistic watermarking algorithms modify the text, they withstand all formatting-based attacks. However, depending on the algorithm, the payload may be lost if the adversary performs a content-based attack. Structural algorithms are usually more fragile. Nonetheless, they may be preferable in some contexts. Since they do not alter the text, therefore the meaning of the document is surely preserved.

Linguistic algorithms require a lexical database to represent the language of the document. WordNet \[23\] is among the most used. Originally developed in English in the Cognitive Science Laboratory of Princeton University, it has now expanded to more than 200 languages. WordNet links words (sequence of characters) and their senses into semantic relations including synonyms, hyponyms, and meronyms. Synonyms are grouped into ‘synsets’ (or synonym rings) with short definitions and usage examples.

Portable Document Format (PDF) is the ISO standard for the representation of electronic documents [14]. Documents are presented always in the same manner, independently from the user’s system. A PDF file includes at least four elements: the header, the body, the cross-reference table and the trailer. In particular, the body of a document represents the file’s contents and is constituted by a sequence of indirect objects (i.e. objects that are stored elsewhere in the file with respects to where they are referenced).

PDF defines several operators to dictate how text is showed and positioned in a document. The Tf operator specifies the font. Tc and Tw define respectively character and word spacing. Tj shows a text string based on the aforementioned parameters. TJ is the more advanced version of Tj, as it can control the positioning of individual characters inside a string.

2.1 Word Similarity

There are several similarity functions that analyse the closeness of two senses, many of which are based on WordNet. Let \(\text{lcs}(x, y)\) be a function returning the least common subsumer (i.e. the most specific ancestor) of senses \(x\) and \(y\), let \(\text{ic}(x)\) be a function returning the information content (IC) of sense \(x\), and let \(\text{depth}(x)\) be the function returning the depth of node \(x\). Obviously, each of these functions returns the same value for all senses in a synset.

The Wu-Palmer similarity considers the depth of the LCS in relations with the depth of the sense. It goes from 0 to 1 and is defined as

\[
\text{wup}(\langle w_x, s_x \rangle, \langle w_y, s_y \rangle) \triangleq \frac{2 \cdot \text{depth}(\text{lcs}(\langle w_x, s_x \rangle, \langle w_y, s_y \rangle))}{\text{depth}(\langle w_x, s_x \rangle) + \text{depth}(\langle w_y, s_y \rangle)}.
\]
The Leacock-Chodorow scales the depth of the LCS with respect to the maximum depth of the taxonomy in which the senses occur:

\[
\text{lch}(w_x, s_x, w_y, s_y) \triangleq \log \frac{\text{len(path}(w_x, s_x), w_y, s_y))}{2 \cdot \text{maxLength}(w_x, s_x, w_y, s_y))}.
\]

The Resnik similarity corresponds to the information content of the least common subsumer:

\[
\text{res}(w_x, s_x, w_y, s_y) \triangleq \text{ic}(\text{lcs}(w_x, s_x, w_y, s_y)).
\]

Its lower bound is 0 whereas the upper bound is \(\log N\), where \(N\) is the number of senses in the taxonomy. The Jiang-Conrath similarity is defined as

\[
\text{jcn}(w_x, s_x, w_y, s_y) \triangleq \frac{\text{ic}(w_x, s_x) + \text{ic}(w_y, s_y)}{\text{ic}(\text{lcs}(w_x, s_x, w_y, s_y))} - 2 \cdot \text{ic}(\text{lcs}(w_x, s_x, w_y, s_y))^{-1}.
\]

If the senses are in the same synset, jcn encounters a singularity. However, \(+\infty\) is not returned even in those environments that supports it, such as Python and R. Instead, 1 is returned. Lin similarity is another extension of Resnik’s:

\[
\text{lin}(w_x, s_x, w_y, s_y) \triangleq \frac{2 \cdot \text{ic}(\text{lcs}(w_x, s_x, w_y, s_y))}{\text{ic}(w_x, s_x) + \text{ic}(w_y, s_y)}.
\]

By convention, all three information-content-based similarity functions span from 0 to 1.

Path-based similarities (Wu-Palmer and Leacock-Chodorow) cannot be meaningfully compared to ic-based similarities. Nonetheless, based on empirical measures, we know that Leacock-Chodorow is more respondent to reality than Wu-Palmer and Resnik performs worse than Jiang-Conrath and Lin [19].

3 Approach

Traitor tracing has specific assumptions and requirements. The original work cannot be destroyed because a new watermarked version needs to be generated at each access. In addition, we assume to be working with official documents that need to be preserved. They can be discarded only when they cease to be relevant, which is when the traitor tracing mechanism is not required any more. Therefore, we can safely use both blind and non-blind watermarking schemes. Semi-blind algorithms are not suited to traitor tracing because the embedded payload is not known when checking a leaked document.

Another vital requirement is high embedding effectiveness. The used algorithm should reliably embed all possible payloads in all admissible objects. Obviously, this result is unattainable. In real life, textual works may be even a few words long, thus impossible to be dependably watermarked by a robust technique. Since we use three watermarking algorithms, it is probable that at least one of them (especially the font-based one) will successfully embed the payload.
This consideration takes us to the next requirement: robustness. We do not distinguish between normal content processing and deliberate attacks because the result is the same: watermark removal. Since we conform to Shannon’s maxim, we assume that the adversary has complete knowledge of the used algorithm except for the secret key. Obviously, when one or more algorithms fail to embed the payload, robustness decreases because they cannot withstand some types of attack that it normally could.

The document watermarking technique we propose is composed by three separate algorithms that work in synergy: the first is linguistic, the second is structural and the third is font-based. We designed and implemented this technique based on the PDF 2.0 specification. Nonetheless, it can be expanded to other formats with new document parser/ embedder algorithms.

3.1 Adversary

The proposed algorithm was designed under the assumption that the adversary must leak a credible file to maintain their reputation. As such, they can either publish the entire processed document (after having performed formatting- and content-based attacks) or just a portion visually identical to the original. This behaviour is inspired by the code of conduct of real-world leakers such as WikiLeaks or the press. However, it fails to capture more prosaic cases, such as disgruntled employees. Those adversaries do not care about neither credibility nor reputation. Their only goal is to cause the maximum damage to their (possibly former) employer. Since they increase the set of allowed attacks almost limitlessly, they were excluded from the chosen adversary model.

3.2 Linguistic

A homograph is a word that is spelled exactly as another word but has different meaning. For example, ‘bear’ can signify both the carnivore mammal and to carry. Thus, a homograph belongs to multiple synsets. The use of homographs for text watermarking was first proposed by [28]. Performing synonym substitution with homographs increases ambiguity. Consequently, erasing the payload by restoring the original words is more difficult. While the algorithm proposed work is quite robust, it was not specifically designed for traitor tracing. As such, we can design a new algorithm that is better suited to our use case.

While we use WordNet to define the watermarking technique, it is not a fixed requirement: we can seamlessly replace it with any other framework that uses a similar concept. Better yet, organisations can use natural language processing to create synsets from a specific corpus in order to adapt the algorithm to their specialised jargon.

---

4 Some dictionaries impose that the two words must also have different origin. However, it is not relevant in this context.
Graph Creation Let $G$ be a graph where vertices represent $\langle\text{word, sense}\rangle$ pairs and edges indicate that their endpoints are in the same synset. Using $G$ and a secret key $k_G$, we create a new weighted graph $G_w$. This step is computationally expensive, but is performed a single time for all embedding and extractions that use the same WordNet version and $k_G$. Moreover, $G$ and edge weights are independent of the secret key. Therefore, they can be re-used in all computations of $G_w$ that are based on the same $G$.

We collapse all vertices with the same word representation in a single vertex. We leave the edges as they are: two vertices are linked if and only if their senses share at least a synset. Then, we assign a weight to the vertices that reflects the similarity between the endpoints. Let $S(x)$ be a function that returns all senses of word $x$. Given two neighbours $x$ and $y$, the weight of the edge linking them is

$$\text{weight}(x, y) \triangleq \frac{\sum_{s_x \in S(x)} \sum_{s_y \in S(y)} \text{sim}(\langle x, s_x \rangle, \langle y, s_y \rangle)}{|S(x)| \cdot |S(y)|},$$

where sim is a similarity function between two senses. There are several such metrics, see sec. 2.1 for a brief review of some of them. Functions whose codomain is $[0, 1]$ are the most appropriate for the watermarking algorithm. Therefore, the two choices among those analysed are Jiang-Conrath and Lin. While in our implementation we chose the latter, the former is still acceptable.

Finally, we label all homographs with 0 or 1 in a way that each word has approximately the same number of 0- and 1-homographs as neighbours. For example, we could use the least significant bit of a cryptographic hash function with key $k_G$. If the hash function is resistant to preimage attacks, then the watermarking algorithm withstands to Single-Watermarked-Image-Counterfeit-Original (swico) and Twin-Watermarked-Images-Counterfeit-Original (twico) attacks. Even though such a property is not necessary in our use case, it may still be desirable. In order to complicate the adversary’s task, we can label the edges instead of the vertices. In this way, the hash function can accept the concatenation of the endpoints as input.

Since $G_w$ is created deterministically, it is not a problem if an attacker compromises the framework and erases $G_w$, as long as $G$ and $k_G$ are safely stored or can be re-computed.

Embedding Let neighbours$(x, b)$ be the function that returns all neighbours of $x$ labelled with $b$. Then, alg. 1 embeds a payload $p'$ in a document $d$. To streamline the pseudocode, the algorithm is in-place. Since the pdf parser and embedder is a distinct algorithm, this simplification has no practical consequences.

Even though the algorithm as presented is perfectly suitable for documents with no strict formatting, it may not produce acceptable results when applied to justified documents. In fact, we are not imposing that each row in $d_w$ must have the same width as the corresponding row in $d$. Let $F_j$ be the set of indices corresponding to words following and in the same line of $d[j]$ that are not untouchable:

$$F_j \triangleq \{l \mid l > j \land d[l] \text{ in same line of } d[j] \land \neg u[l]\}.$$
Algorithm 1: Linguistic embedding.

**Data:** original document $d$ as an array of words;
payload $p'$ as defined in sec. 3.5;
array $u$ containing whether the corresponding word in $d$ can be replaced;

**Result:** whether the embedding succeeded

1. $i \leftarrow 0$ \hspace{1em} // counter for $p'$
2. $j \leftarrow 0$ \hspace{1em} // counter for $d$
3. While $i < |p'|$ do
   1. If $j = |d|$ then
      1. // document ended but
         // $p'$ was not fully embedded
         1. Return ⊥
   2. If $d[j] \notin G_w \lor u[j]$ then
      1. // word cannot be replaced
         1. $j \leftarrow j + 1$
         2. Continue
   3. $d[j] \leftarrow \arg \max_{w \in \text{neighbours}(d[j], p[i])} \text{weight}(d[j], w)$
   4. $i \leftarrow i + 1$
   5. $j \leftarrow j + 1$
4. // embed the error-correcting code
   1. // see sec. 3.2
   2. embedEcc($d, p', j + 1$)
5. Return ⊤

Moreover, let $P_j$ be the set of indices corresponding to words preceding and in the same line of $d[j]$: $$P_j \triangleq \{ l \mid l < j \land d[l] \text{ in same line of } d[j] \}.$$ Then, the total number of letters before $d[j]$ (or $w$) is $P_j \triangleq \sum_{l \in P_j} |d[l]|$ (respectively $P_{wj} \triangleq \sum_{l \in P_j} |d_w[l]|$).

We could weight the to-be-maximised function with a coefficient $q$ defined as

$$q(j) \triangleq \begin{cases} 
0 & \text{if } |F_j| = 0 \land \
- (P_j = P_{wj} \land |d[j]| = |w|) & \text{if } |F_j| \neq 0 \\
1 - \left| \frac{P_j + |d[j]| - P_{wj} - |w|}{|P_j|} \right| & \text{if } |F_j| = 0 \land P_j = P_{wj} \land \\
1 & |d[j]| = |w| 
\end{cases}$$
and impose that \( q \) must be strictly positive, at least for the last word. If the last word has no homograph neighbour that meets the requirement, we can choose a non-homograph one and renounce to embed a bit. Even though such a stratagem undoubtedly increases the embedding effectiveness, there is still room for improvement. A simplification that still yields acceptable results is to impose that the watermarked line must have the same length or be shorter than the original one. Then, it is up to the PDF embedder to produce a document with the required structure.

**Sphinx of black quartz, judge my vow.**

Sphinx of black quartz, judge my vow.

**Fig. 1.** Pangrams of a mono-spaced (above) and a variable-width font. Characters such as ‘i’ and ‘l’ are narrower in the lower writing.

The proposed approach works best with mono-spaced fonts, whose characters each occupy the same amount of horizontal space. However, proportional fonts are more commonly used. Thus, we should expect characters to have different sizes. Consequently, the only reliable method to impose proper formatting is to choose the line length and the minimum and maximum inter-word spaces, parse the font to retrieve the character widths and calculate if the watermarked text is acceptable. If it is not, then replace one or more words with ones that similarity-wise are slightly worse but fit better in the line. This approach is computationally expensive, but it is the one with the highest embedding rate. To achieve optimal results, kerning must be taken into account. Otherwise, lines could erroneously be identified as unacceptable. Still, discrepancies should be so small to have no practical consequences in the majority of documents.

**Extraction** Let \( \text{neighbours}(x) \) be the function that returns all neighbours of \( x \), let \( \text{homograph}(x) \) be the function that checks whether \( x \) is a homograph and let \( \text{extractBit}(x) \) be the function that extracts the payload bit from a homograph \( x \). Let \( \text{checkInserted} \) and \( \text{checkDeleted} \) be the functions that check that at most \( \lambda \) words were respectively inserted or deleted by the adversary\(^5\). The latter also returns the number of deleted payload-bearing words, so that we can guess the erased payload bits. Each guessed bit is correct with probability \( \frac{1}{2} \).

Algorithm 2 (and its continuation, alg. 3) extracts a payload \( p'' \) from the document \( d_w \). Error correction is left to external components. The algorithm automatically recovers synchronisation if the adversary changes, inserts or deletes words. When possible, it also tries to recover the removed payload. Since we assume that adversaries want to preserve the original meaning, we check for word

\(^5\) Obviously, we could also choose two different coefficients for insertion and deletion checks.
Algorithm 2: Linguistic extraction. Part 1: untouched words.

Data: original document $d$ as an array of words;
watermarked document $d_w$ as an array of words;
array $u$ containing whether the corresponding word in $d$ can be replaced; max number $\lambda$ of words that could have been inserted or deleted by the adversary;

Result: extracted payload $p''$ (see sec. 3.2)

$p'' \leftarrow []$

$i \leftarrow 1$ // counter for $p''$

$j \leftarrow 1$ // counter for $d$

$l \leftarrow 1$ // counter for $d_w$

while $l \leq |d_w|$ do

  if $u[j] \vee d[j] \notin G_w$ then

    if $d[j] = d_w[l] \vee d[j] \in \text{neighbours}(d_w[l]) \vee \exists r : d[j], d_w[l] \in \text{neighbours}(r)$ then

      $j \leftarrow j + 1; l \leftarrow l + 1$

    else if $x \leftarrow \text{checkInserted}(d[j], d_w, l, \lambda)$ then

      // untouchable word is skipped

      $j \leftarrow j + 1; l \leftarrow l + x + 1$

    else if $x, y \leftarrow \text{checkDeleted}(d_w[l], d, j, \lambda)$ then

      $p''[i \text{ to } i + y - 1] \leftarrow \text{random}([0, 1])$

      $i \leftarrow i + y; j \leftarrow j + x$

    else

      throw exception // Lost sync

  end

  continue

end

insertion before deletion. We presume that a word was inserted if

$$d[j] = d_w[l + 1] \vee d[j] \in \text{neighbours}(d_w[l + 1]) \vee \exists r : d[j], d_w[l + 1] \in \text{neighbours}(r).$$

The word-deletion criterion is equivalent. Both criteria can be easily generalised up to $\lambda$ consecutive inserted or deleted words. However, the algorithm loses synchronisation when the adversary consecutively inserts and deletes words. It is possible to handle even those extreme cases; however, it may be advisable to manually check the document. Using NLP decreases de-synchronisation rate, but may require human supervision.

If synchronisation is lost with respect to $\lambda$, the algorithm throws an exception. Then, the user can choose to either increase the parameter or manually edit the document. We can also design a simplified version without \text{checkDeleted} and \text{checkInserted}. Whenever synchronisation is lost, the algorithm assumes that
Algorithm 3: Linguistic extraction. Part 2: payload-bearing words.

```plaintext
if \( d[j] = d_w[l] \) then
    // adversary removed payload bit
    \( p''[i] \leftarrow \text{random}([0,1]) \);
    \( i \leftarrow i + 1; j \leftarrow j + 1; l \leftarrow l + 1 \)
else if \( \text{homograph}(d_w[l]) \land d_w[l] \in \text{neighbours}(d[j]) \) then
    \( p''[i] \leftarrow \text{extractBit}(d_w[l]) \);
    \( i \leftarrow i + 1; j \leftarrow j + 1; l \leftarrow l + 1 \)
else if \( \exists r : \text{homograph}(r) \land d[j], d_w[l] \in \text{neighbours}(r) \) then
    // may be wrong if multiple \( w \)
    \( p''[i] \leftarrow \text{extractBit}(r) \);
    \( i \leftarrow i + 1; j \leftarrow j + 1; l \leftarrow l + 1 \)
else if \( x \leftarrow \text{checkInserted}(d[j], d_w, l, \lambda) \) then
    \( l \leftarrow l + x \)
else if \( x, y \leftarrow \text{checkDeleted}(d_w[l], d, j, \lambda) \) then
    \( p''[i \text{ to } i + y - 1] \leftarrow \text{random}([0,1]) \);
    \( i \leftarrow i + y; j \leftarrow j + x \)
else
    throw exception
end
return \( p'' \)
```
a single word was inserted. Even though this version is less accurate, it is easier to implement, as we do not need to construct insertion and deletion check.

If we want to use the embedding algorithm proposed for variable-width fonts, it becomes quite difficult for the extraction algorithm to determine whether a word bears a payload. Wet paper codes solve this exact problem, as they are designed for extraction algorithms that do not know which elements carry the payload \[10\]. However, wet paper codes are not suited to traitor tracing, as they assume a passive adversary. Instead, we can use a synchronisation ecc.

**Error Recovery** The error recovery mechanism depends on the watermarking algorithm. With the one that we initially proposed, it is sufficient to use a Reed-Solomon code with bch view. We define the extracted payload \(p''\) as \(p'' \triangleq p' \parallel \text{ecc}(p')\). The only drawback is that we must decide the number of correctable errors. Since such figure is dependent upon the number of embeddable symbols it can be easily estimated. We start with the number remaining touchable words that can be found in \(G_w\) as ecc size. Then, we decrease it until the embedding is successful.

Unfortunately, the situation is more complex if we decide to embed justified documents that use proportional fonts. Borrowing steganalysis's terminology, we can say that the transmission channel is unknown to the receiver. However, since we assume an active adversary, we cannot use wet paper codes. Instead, we have to use watermark codes, which are designed to correct substitution, insertion, and deletion errors at the cost of a sizeable overhead. In recent years, several efficient implementations have been proposed. In particular, the concatenated synchronisation error correcting code designed by \[29\] is quite promising.

**Tagged Documents** We assumed that documents are not tagged, meaning that the algorithm does not know the specific sense of the words occurring in the document. Tagging must be performed manually by the author (or a qualified user) and is excessively time-consuming to be done on every document. However, authors may be interested in tagging specific documents or words in order to ensure that meanings are not altered. Thus, it may be interesting to expand the watermarking algorithm in order to include tagged documents.

The graph is slightly more complex. Starting from \(G\), for each word we add a generic vertex representing the entirety of its senses. Let \(w\) be a valid word, then we create an edge linking \(\langle w', s \rangle\) and \(w\) for each vertex \(\langle w', s \rangle\) representing a pair in the same synset of one of the meanings of \(w\). Each vertex is weighted according to the function

\[
\text{weight}(\langle x, s_x \rangle, y) \triangleq \sum_{s_y \in S(y)} \text{sim}(\langle x, s_x \rangle, \langle y, s_y \rangle) / |S(y)|
\]

where everything is defined as before. Finally, we can delete the original edges. The remaining portion of the graph creation process, the embedding algorithm and the extraction one are left untouched.
Watermarked documents produced from tagged data are usually of higher quality than those produced from non-tagged documents. As mentioned, we cannot expect organisations to manually tag their sensitive documents. However, several sense-identifying neural networks have been presented in recent years. In particular, EWISER was the first to reach the threshold of 80% correctness [4], which is comparable to how humans perform. Determining whether EWISER and analogous networks actually improve the watermarking algorithm require further study.

3.3 Structural

In the previous section we assumed that the original document is retained, thus we could use a non-blind watermarking algorithm. Unfortunately, we cannot replicate the reasoning in this context. Since the document is modified by the synonym substitution, we are forced to choose a blind algorithm.

The technique proposed by [16] is an ideal candidate. In [16], words are divided into classes and labelled based on width comparison with neighbouring words. Then, lines are divided into segments of $s$ consecutive words such that the first and the last word of each segment are shared with its neighbours. Segments are divided into classes and labelled based on the labels of the words they contain. The same amount of information is carried independently by each segment in its inter-word space statistics. The payload is embedded by shifting non-shared words in each segment. Designing embedding and extraction rules must consider the $s$, the number of segment classes and the payload size.

Conversely to the linguistic algorithm, there is the concrete possibility that we can extract the payload from a single section. According to the adversary model, if the adversary does not publish the entire documents, they cannot alter its visual appearance. Therefore, we can design word classes based not only on relations with adjacent words, but also on relations with corresponding words in the original documents (e.g. if the word carries a payload bit). Obviously, we cannot increase the number of classes ad infinitum, lest the decrease of embedding effectiveness caused by the under-representation of specific segment classes.

3.4 Font-Based Algorithm

There are several PDF metadata-watermarking algorithms. Some use comments, others use invisible objects, still others modify the embedded fonts. A technique similar to [26] is ideal. Not only it is resistant to printing, it also splits the payload among several characters. Thus, it is not removed when the adversary extrapolates a portion of the document. Conversely, techniques that change glyphs in specific locations, such as the first proposed in [13], are not well-suited to the proposed adversary model. They do not withstand the extrapolation of a document portion and the synonym substitution is more robust when the adversary publishes the whole document.

If altering character shapes is not feasible, a non-printing-resistant alternative is changing the font’s character map. The payload can be represented as an
integer, thus we can construct an equivalent self-inverting permutation as described in [8]. Then, we can embed the payload by changing the glyphs’ (or the character codes’) order according to the permutation. The technique is not as conspicuous as it may seem. The PDF standard specifies copy protection. However, it must be enforced by a compliant reader. Thus, a common stratagem is to alter the cmap so that relations between glyphs and character codes are scrambled. Obviously, the text needs to be modified so that the document retains its original visual appearance. The adversary cannot seamlessly swap the font with a similar-looking alternative, otherwise the text would be garbled. Thus, they may settle for publishing an image of the document, preserving the structural watermark.

3.5 Payload

Using the user id as payload is the easiest way to perform traitor tracing with watermarks. However, it has a serious drawback that cannot be overlooked. Suppose that an attacker gains access to a user account. Then, the real user can divulge any document, blaming the attacker for the leak. Secure logs are a deterrent, but the user may be able to mount a convincing defence based on the severity of the attack.

The obvious solution is to change user identifiers after every attack. In order to have certain accountability, all identifiers must be changed even if the intrusion was not successful. However, it is a non-trivial logistical problem when the number of accounts is vast. In some cases, the user id is linked to external factors (such as the social security number), thus changing it is impossible.

Therefore, payloads containing only the user id do not offer sufficient accountability. At least the download timestamp must be included. In the following sections two possible payload for traitor tracing will be presented, each with its own pros and cons.

Log-Independent Payload In this section we will present a payload type that does not rely on external logging mechanisms. As showed, we need to embed in a document at least the user id and the time of download. In order to increase embedding effectiveness, the payload must be as small as possible. The user id typically is decided by external or logistic requirements, thus we will focus only on the timestamp. We can choose from several time encodings, but we will take into consideration only the two that require the least storing space.

ISO 8601 is the international standard that defines the textual representation of dates, times, and intervals. There are several string formats, of which the most compact is [YYYY][DDD][hh][mm][ss]Z. Storing it as an ASCII string requires 105 bit, so using it in the payload is not feasible. However, since we fix the format and impose that all times are UTC, we can omit the time T and time zone Z indicators. All remaining characters are numeric, therefore we can encode each component separately as an integer. In total, this technique requires 38 bit. If we use only the last two digits of the year ([YY][DDD][hh][mm][ss]), we can decrease the space requirement to 33 bit.
Unix-like systems use Unix time, which is the number of seconds that have elapsed since 1970-01-01T00:00:00Z, leap seconds excluded. Traditional Unix time encoding uses a 32 bit signed integer and can represent times from 1901-12-13T20:45:54Z to 2036-01-19T03:14:08Z. It is a compact representation, but the maximum date is too close to be used in new applications. Modern Unix systems use 64 bit, which can represent a much wider range of times. However, it requires too much space to be used in the payload. Since we do not care about past dates, the best solution is to use a 32 bit unsigned integer, which can store a time up to 2106-02-07T06:28:15Z.

Both solutions are non-standard to some extend, even though there are historical examples of Unix times stored in unsigned integers. As such, the latter technique is the preferred one. The former’s only advantage is that it correctly identifies leap seconds, but in the majority of applications such a high sensitivity is not required. We can use even less storage size by choosing an arbitrary epoch zero. However, this approach requires external information, partly defeating the purpose of having a log-independent payload.

Since the user id is fixed and the timestamp is known, an aggressor can perform chosen-message attacks. It should not be a problem if the algorithm used to encrypt the payload is sound. Nonetheless, we can add an 8 bit random integer to prevent the aforementioned attacks.

Log-Dependent Payload  Contrary to the log-independent one, the payload scheme presented in this section relies upon a log server. We suppose that download logs are stored in a relational database that includes a table with at least the following columns:

- **download_id (bigint)**: ID of the download. It constitutes the actual watermark payload. It must be randomly generated, so that an aggressor cannot perform chosen-message attacks.
- **document_id (bigint)**: ID of the document. It must uniquely identify a document, independently from the specific version.
- **user_id (bigint or string)**: ID of the user that downloaded the document.
- **timestamp**: date and time of download. Second precision is sufficient.
- **ip_addr (inet or equivalent)**: IPv4/IPv6 address from which the document was downloaded from.

This information allows to uniquely identify a download and provides all elements required to trace it back to the offending user.

Assuming that identifier and time fields are 8 B long and that inet fields are 7 B long for IPv4 addresses (or 19 B for IPv6), then the total row size is 39 B (or 51 B). Storage is relatively inexpensive, thus we can freely add other pieces of information that may be relevant in a later investigation (e.g. the user’s security clearance). The embedded payload contains only `download_id`.

When designing the log database, we can choose between two unique constraints. The easiest and most reliable method is to choose `download_id` as (primary or unique secondary) key. However, it greatly reduces the number of
downloads we can watermark with a given download_id size. Choosing a larger payload affects negatively imperceptibility and embedding effectiveness, which are the strong points of log-dependent payloads. The other technique consists in choosing the combination download_id-document_id as unique key. It is more space efficient, but it increases the complexity of the watermarking extraction algorithm.

Log-dependent payloads are smaller than log-independent ones. This characteristic plays a pivotal role on imperceptibility and embedding effectiveness in short documents. As such, in some cases they are the only suitable solution. Nonetheless, they rely on external servers. If logs can be altered, high-privileged users can cover their tracks without performing illegal operations. The problem is mitigated by a clear separation between users and system administrators. However, it is not resolved: a user and an administrator can ally in order to circumvent the protections. The only reliable solution is to make the logs unchangeable, so that all operations can be audited.

Payload Choice We assume that the leaker wants to be credible. They can either publish the entire document (after having performed formatting- and content-based attacks) or just an untouched section.

Let us analyse the former case. If the document is subject to formatting-based attacks, we can assume that structural and font-based payloads have been removed. Thus, it is indifferent which payload we choose for those two algorithms. Since the burden of traitor tracing is placed entirely on the linguistic algorithm, it is advisable to choose the log-independent payload for it if the length of the document allows it.

Now, let us focus on the latter case. Only a section of the document is published by the adversary, therefore the linguistic payload has been removed. Given the structural algorithm’s construction, a small payload is advisable. Therefore, the log-dependent one is the best choice. Conversely, the metadata-based algorithm does not have specific size constraints. Thus, we are free to choose the log-independent payload in order to increase, although marginally, robustness.

Encryption The watermarking algorithm must guarantee payload confidentiality and authenticity. Therefore, we must adopt authenticated encryption (AE). There are three main AE approaches: encrypt-then-MAC, encrypt-and-MAC and MAC-then-encrypt. Since the first is the most secure [3], it is the one we will adopt.

The payload is encrypted using the function Enc: \( P \times K \rightarrow C \), \((p, k) \mapsto c\), then the message authentication code (MAC) is generated from the ciphertext by the function Tag: \( C \times K \rightarrow \Phi \), \((c, k') \mapsto \phi\). The final payload \( p' \triangleq c \parallel \phi \) is just the concatenation of the ciphertext and the MAC. In order for the authenticated
encryption to be resistant to all kind of attacks, \texttt{Enc} must be IND-CPA\textsuperscript{6} and \texttt{Tag} must be strongly unforgeable.

Authenticated encryption applies to both symmetric and asymmetric cryptography. Both have readily available secure implementations. Symmetric encryption is usually faster than asymmetric, although the latter may be preferable from an ethical standpoint (see sec. 3.6).

3.6 Chilling Effect

A whistle-blower is a person that informs someone in authority that offences are being committed, especially in a government department or a large company. In order for the whistle-blower to be credible, they must have compelling evidence to support their allegations, which the regulating body can use to confirm such claims. A case would never continue on legally, or ever be reported by news services, without substantial documentation.

Even though whistle-blowers’ identities are usually secret and persecuting whistle-blowers is illegal in many countries, being one is not risk free. There have been several reports of whistle-blowers being retaliated against from those they accused or alleged of wrongdoing. As a result, potentials whistle-blowers are often discouraged from reporting their concerns for fear of reprisals \cite{9}. The watermarking algorithm we present may become yet another impediment to whistle-blowing.

This is most concerning when the whistle-blower is employed in a government agency. Those who may be adversely affected by allegations are typically those in a position of authority. They are the same people that have access to the case files, therefore they can discover the whistle-blower’s identity by extracting the watermark payloads. The natural solution is to protect the payloads through asymmetric encryption. The decrypting key should be known only by an external trusted entity, which must use it exclusively when ordered by an impartial third party (ideally a judge). However, since there is currently no law that protects whistle-blowing identities from legitimate discovery attempts, the adoption of protection mechanisms rests entirely on the willingness of the management body.

4 Implementation

The implementation is composed by two parts: the watermarking algorithm in the strict sense and the PDF parsing/embedding applicative. The former is the same for all kinds of files, while the latter is dependent on the document formatting. Figures 2 and 3 show a PDF document before and after the embedding of a 3B payload with no \texttt{ecc}.

\textsuperscript{6} A cryptosystem is indistinguishable under chosen-plaintext attack (IND-CPA) if every probabilistic polynomial time adversary has only a negligible advantage over random guessing.
Before the advent of the Internet, digital watermarking was considered a minor branch of computer science. The literature reflects this poor consideration: formal studies were uncommon, as technological advancement was mostly carried out by patents. All changed in the mid '90s.

Before the Internet, sending files was a troublesome task. Public bodies, large companies and academic institutions had their own private intranets, some interconnected one other but normal people had no such luxury. Therefore, cryptography was more than sufficient to secure digital assets. Publishing companies used to encrypt their works and send them to the paying customers, which were also provided the decrypting keys through a digital rights management (DRM) system. If the client wanted to share its purchase, they had to do it physically, with the same obstacles as traditional publishing means.

However, the Internet affected immensely the picture. Transferring small and medium files was extremely easy and did not require noteworthy computer skills. Thus, encryption was still a required technique to secure digital assets, but it was ineffective if used alone. Since the unencrypted file was completely unprotected, a paying customer could freely share it with countless people across the globe. Music piracy was the first widespread form of online piracy thanks to the small size of audio files. Accordingly, record labels were the first to explore ways to make customers accountable for their actions. When publishing companies grasped the inefficacy of their current methodologies, they expressed a clear interest in digital watermarks. Few pioneers had already patented watermarking algorithms for audio files, but they were not commonly used. The increased demand produces a dramatic increment in academic studies and patents, which favoured the design adoption of digital watermarking for other types of works in later times.

With the improvement of the Internet, videos took the spotlight in online piracy. Copy-protections of physical media were always easily circumvented, so traditional publishing companies were the first to take an interest in digital watermarking. When transfer times reduced further, online renting and streaming services joined the effort. Nowadays, most of the copyrighted videos are distributed through DRMs that automatically embed a watermark containing the user's id into the bitstream, an effective traitor tracing mechanism.

However, there is a medium that is still difficult to watermark: text. Textual works are not bound to a single physical form, so traditional watermarking techniques cannot be seamlessly used. It is possible to transform the text into an image and watermark it, but the image can be easily transformed back into the original non-watermarked text. Alternatively, it is possible to embed the watermark into the formatting, which can nevertheless be easily changed, destroying the watermark. An effective solution to this problem is to change the texts, either introducing errors or replacing words (or entire sentences) with alternative formulations. Ultimately, there is not yet a digital watermarking algorithm that is robust, secure and does not alter the text.

Fig. 2. A justified PDF document.

4.1 Watermarking Algorithm

We chose to implement the watermarking technique in Python thanks to its flexibility and its widespread adoption. The watermarking package is composed by three distinct sub-packages, each corresponding to one of the presented algorithms.

Implementation of structural and cmap-based algorithms is straightforward and follows closely sec. 3.3 and 3.4. On the contrary, implementations of the linguistic algorithm must include natural language processing. My original intention was to use only spaCy [12] with a WordNet plugin. However, we had to adopt LemmInflect [15] for lemmatisation and inflection and NLTK [5] for word similarity. We adopted NLTK rather than Wn [11] because the latter does not implement ic-based similarity functions yet. WordNet distinguished between several word classes, thus it is necessary to select only the neighbours with the correct part-of-speech (POS) tag. We can use POS tags during payload extraction only if the adversary has the same knowledge of NLP techniques. Otherwise, we may wrongly identify a word as deleted. An issue concerns the tokenisation of the document. While phrasal verbs can be easily identified with POS tags (RP in the Penn Treebank [20]), generic multi-word tokens may be wrongly parsed as separate entities (e.g. the adverb ‘a lot’ may be interpreted as the indefinite article ‘a’ and the noun ‘lot’).

In order to produce watermarked documents visually similar to the originals, to create an intermediate PDF file after the execution of the linguistic algorithm
Before the advent of the Internet, digital watermarking was reckoned a modest branch of computer science. The literature reflects this pitiable consideration: formal studies were uncommon, as technological advancement was carried out mostly by patents. All changed in the mid '90s.

Before the Internet, placing files was a troublesome task. Public bodies, heavy companies and academic initiations had their own private intranets, some interconnected one other, but normal people had no such luxury. Therefore, cryptography was more than sufficient to secure digital assets. Publishing companies used to encrypt their works and place them to the giving customers, which were also provided the decrypting keys through a digital rights management (DRM) system. If the client wanted to share its purchase, they had to doing it physically, with the same obstacles as traditional publishing means.

However, the Internet dissembled enormously the picture. Transferring little and medium files was extremely easy and did not require noteworthy computer skills. Thus, encryption was still a required technique to fix digital assets, but it was ineffective if used alone. Since the unencrypted file was completely unprotected, a giving customer could freely share it with countless people across the globe. Music piracy was the first widespread shape of online piracy thanks to the little size of audio files. Accordingly, record labels were the first to explore ways to make customers accountable for their actions. When publishing companies grasped the inefficacy of their current methodologies, they showed a clear interest in digital watermarks. Few pioneers had already patented watermarking algorithms for audio files, but they were not commonly used. The increased demand produces a dramatic increment in academic studies and patents, which favoured the design adoption of digital watermarking for other type of works in later times.

With the improvement of Internet, videos accepted the spotlight in online piracy. Copy-protections of physical media were always easily circumvented, so traditional publishing companies were the first to accept an interest in digital watermarking. When transfer times cut further, online renting and streaming services linked up the effort. Nowadays, most of the copyrighted videos are distributed through DRMs that automatically embed a watermark containing the user's id into the bitstream, an effective traitor tracing mechanism.

However, there is a medium that is still difficult to watermark: text. Textual works are not bound to a single physical form, so traditional watermarking techniques cannot be seamlessly used. It is possible to embed the text in an image, and sometimes in the formatting, which can make it more difficult to detect, but watermarking text is much more challenging than watermarking audio or video. There is not yet a digital watermarking algorithm that is robust, secure and does not alter the text.

**Fig. 3.** A watermarked version of the document in fig. [2]. The payload is OxA6A3CA. Justification was not enforced.

is recommended. In this way, the embedder can adjust the formatting before the second algorithm alters inter-word spaces. We have the best results when the original document was automatically produces from a master template. Then, the embedder can call the formatting applicative to produce a perfect document.

**Homograph Identification** Homograph identification deserves a brief aside. Trivially checking whether a word belongs to multiple synsets is formally correct but does not yield satisfactory results. Let us analyse the verb ‘journey’. Even though it belongs to two synsets, travel.v.02 and travel.v.04, it is not a homograph. Although the synsets have two different formal definitions, they represent approximately the same concept and contain the same words. Therefore, ‘journey’ lacks the necessary ambiguity to be a payload-bearing word. The culprit is WordNet’s definition granularity, which is excessively fine in some context. Inter-annotator agreement, the percentage of words tagged with the same sense by two or more human annotators, is estimated between 67% and 80% [24].

In our implementation, we consider a word as a homograph if it belongs to at least two disjoint synsets (i.e. two of its synsets have no words in common).

---

7 Respectively ‘undertake a journey or trip’ and ‘travel upon or across’.
8 ‘journey’ and ‘travel’.
While this technique decreases false positives, it does not solve the problems of false negatives. Let us consider the noun ‘street’. It belongs to five synset, including the nearly identical ‘a thoroughfare (usually including sidewalks) that is lined with buildings’ and ‘the part of a thoroughfare between the sidewalks; the part of the thoroughfare on which vehicles travel’. However, none of the five synsets contains words other than ‘street’, not even ‘thoroughfare’. This discrepancy is once again caused by WordNet’s granularity. Several coarse sense inventories have been proposed, but their use in the watermarking algorithms requires further study. There is the risk of choosing an incorrect replacement if the granularity is too coarse or the inventory is not well-suited to the jargon used by the organisation.

4.2 Parsing and Embedding Algorithm

The parsing/embedding algorithm must adapt to document’s typographical characteristics, e.g. section levels, paragraph modifiers and justification. Fortunately, all corporate PDF documents are generated from a limited number of master templates. A parsing and embedding algorithm based on a template’s structure should work seamlessly with all derived files. As a proof of concept, we decided to focus on documents composed by a single page with no elaborate formatting. Nonetheless, the algorithm can be easily adapted to multi-page documents with a cycle on the pages.

PDF is a standard designed to display final products. Thus, editing existing files is neither easy nor intuitive. The libraries up to the task are quite scarce. There are none in Python, the language in which we implemented the watermarking algorithm. After careful consideration we opted for HexaPDF [17], a Ruby gem.

Fig. 4. The first line of the document in fig.2. Word fragments are in teal and spaces in orange. The last ‘b’ is detached from the rest of the word due to kerning.

Given the simplicity of the document, the parsing mechanism is not complex. Each TJ operator is analysed separately, then results are coalesced into a single array. Word fragments and inter-word spaces are extracted with regular expressions based on parentheses. We chose an arbitrary boundary of 200 pt between kerning and inter-word spaces. Misclassified instances are improbable: the former is two orders of magnitude shorter than the latter.
5 Conclusions and Future Works

Protecting sensitive data is a vital endeavour for companies and government agencies. To this end, they adopt multiple security mechanisms to defend themselves from external and internal attacks. However, employees are harder to control because they have legitimate access to the confidential documents they may divulge. Therefore, any document-sharing service should include a traitor-tracing mechanism, mainly to act as a deterrent: preventing leaks is much more desirable than bringing the source to justice.

In this paper, we presented an invisible watermarking algorithm for PDF files that can be used in traitor-tracing mechanisms. The technique is robust with respect to adversaries that wants to be credible (e.g., newspapers). However, unwanted consequence may arise following the adoption of the presented framework. It may cause a chilling effect, which is the inhibition or discouragement of the legitimate exercise of natural and legal rights by the threat of legal sanction.

From a technical standpoint, there is margin for improvement. The lexical database cannot be easily updated. This is troublesome for expanding organisations, in which the specialised jargon may shift. Moreover, the natural-language-processing portion of the linguistic algorithm is not in par with the state of the art. The most important issue is that components of multi-word elements may be wrongly recognised as separate (e.g., ‘a lot’ is parsed as ‘a’, ‘lot’). Fortunately, NLP algorithms are quite apt at identifying phrasal verbs. Another serious problem is that the chosen homograph is not always the most apt to the sentence. Integrating a word-sense disambiguation technique such as EWISER could be a major enhancement. In addition, in order to mitigate WordNet’s excessively fine granularity, new sense inventories specific for synonym substitution should be created.
Bibliography

[1] Alotaibi, R.A., Elrefaei, L.A.: Arabic text watermarking: A review. International Journal of Artificial Intelligence & Applications (IJAIA) 6(4), 1–17 (2015). https://doi.org/10.5121/ijaia.2015.6401

[2] Atallah, M.J., Raskin, V., Hempelmann, C., Karahan, M., Sion, R., Topkara, U., Triezenberg, K.E.: Natural language watermarking and tamper-proofing. In: Revised Papers from the 5th International Workshop on Information Hiding. pp. 196–212. Springer-Verlag, Berlin/Heidelberg, DE (2002). https://doi.org/10.1007/3-540-36415-3_13

[3] Bellare, M., Namprempre, C.: Authenticated encryption: Relations among notions and analysis of the generic composition paradigm. Journal of Cryptology 21, 469–491 (2008). https://doi.org/10.1007/s00145-008-9026-x

[4] Bevilacqua, M., Navigli, R.: Breaking through the 80% glass ceiling: Raising the state of the art in word sense disambiguation by incorporating knowledge graph information. In: Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics. pp. 2854–2864. Association for Computational Linguistics (2020). https://doi.org/10.18653/v1/2020.acl-main.255

[5] Bird, S., Klein, E., Loper, E.: Natural Language Processing with Python. O’Reilly Media, Sebastopol, CA, US (2009), https://www.nltk.org

[6] Brassil, J.T., Low, S., Maxemchuk, N.F., O’Gorman, L.: Electronic marking and identification techniques to discourage document copying. IEEE Journal on Selected Areas in Communications 13(8), 1495–1504 (1995). https://doi.org/10.1109/49.464718

[7] Brassil, J.T., Low, S., Maxemchuk, N.F., O’Gorman, L.: Hiding information in document images. In: Proceedings of the 29th Annual Conference on Information Sciences and System. pp. 482–489 (1995)

[8] Chroni, M., Nikolopoulos, S.D.: Encoding watermark integers as self-inverting permutations. In: CompSysTech ’10: Proceedings of the 11th International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing. pp. 125–130. Association for Computing Machinery, New York, NY, US (2010). https://doi.org/10.1145/1839379.1839402

[9] European Parliament, Council of the European Union: Directive (EU) 2019/1937 of the European Parliament and of the Council of 23 October 2019 on the protection of persons who report breaches of Union law. Official Journal of the European Union (L305), 17–56 (11 2019), https://eur-lex.europa.eu/eli/dir/2019/1937/oj

[10] Fridrich, J., Goljan, M., Lisonck, P., Soukal, D.: Writing on wet paper. IEEE Transactions on Signal Processing 53(10), 3923–3935 (2005). https://doi.org/10.1109/TSP.2005.855393

[11] Goodman, M.W.: Wn (12 2020), https://github.com/goodmami/wn
[12] Honnibal, M., Montani, I., Van Landeghem, S., Boyd, A.: spaCy: Industrial-strength natural language processing in Python (11 2020). https://doi.org/10.5281/zenodo.1212303

[13] Huang, D., Yan, H.: Interword distance changes represented by sine waves for watermarking text images. IEEE Transactions on Circuits and Systems for Video Technology 11(12), 1237–1245 (2001). https://doi.org/10.1109/76.974678

[14] Document management — portable document format — part 2: PdF 2.0. Standard, International Organization for Standardization, Geneva, CH (2017). https://www.iso.org/standard/63534.html

[15] Jascob, B.: LemmInflect (02 2020), https://github.com/bjascob/LemmInflect

[16] Kim, Y.W., Moon, K.A., Oh, I.S.: A text watermarking algorithm based on word classification and inter-word space statistics. In: Proceedings Seventh International Conference on Document Analysis and Recognition. pp. 775–779. IEEE, Piscataway, NJ, US (2003). https://doi.org/10.1109/ICDAR.2003.1227767

[17] Leitner, T.: HexaPDF (11 2020), https://hexapdf.gettalong.org/

[18] Levy, K.: Watermark fonts (2002), patent No. US20040001606A1, US. Held by Digimarc Corporation

[19] Li, H., Tian, Y., Ye, B., Cai, Q.: Comparison of current semantic similarity methods in wordnet. In: 2010 International Conference on Computer Application and System Modeling (ICCASM 2010). vol. 4, pp. 408–411. IEEE, Piscataway, NJ, US (2010). https://doi.org/10.1109/ICCASM.2010.5619038

[20] Marcus, M.P., Santorini, B., Marcinkiewicz, M.A.: Building a large annotated corpus of english: The penn treebank. Computational Linguistics 19(2), 313–330 (1993). https://www.aclweb.org/anthology/J93-2004

[21] Meral, H.M., Sevinç, E., Ünkar, E., Sankur, B., Sunru Özsoy, A., Güngör, T.: Syntactic tools for text watermarking. In: Proceedings Volume 6505, Security, Steganography, and Watermarking of Multimedia Contents IX. pp. 339–350. SPIE, Bellingham, WA, US (2007). https://doi.org/10.1117/12.708111

[22] Meral, H.M., Sankur, B., Sunru Özsoy, A., Güngör, T., Sevinç, E.: Natural language watermarking via morphosyntactic alterations. Computer Speech & Language 23(1), 107–125 (2009). https://doi.org/10.1016/j.csl.2008.04.001

[23] Miller, G.A.: Wordnet: A lexical database for english. Communications of the ACM 38(11), 39–41 (1995). https://doi.org/10.1145/219717.219748

[24] Navigli, R.: Word sense disambiguation: A survey. ACM Computing Surveys 41(2), 10 (2009). https://doi.org/10.1145/1459352.1459355

[25] Tan, L., Sun, X., Sun, G.: Print-scan resilient text image watermarking based on stroke direction modulation for chinese document authentication. Radioengineering 21(1), 170–181 (2012). https://www.radioeng.cz/papers/2012-1.htm
[26] Thiemert, S., Steinebach, M., Wolf, P.: A digital watermark for vector-based fonts. In: Proceedings of the 8th Workshop on Multimedia and Security. pp. 120–123. Association for Computing Machinery, New York, NY, US (2006). https://doi.org/10.1145/1161366.1161387

[27] Topkara, M., Topkara, U., Atallah, M.J.: Information hiding through errors: A confusing approach. In: Proceedings Volume 6505, Security, Steganography, and Watermarking of Multimedia Contents IX. pp. 321–332. SPIE, Bellingham, WA, US (2007). https://doi.org/10.1117/12.706980

[28] Topkara, U., Topkara, M., Atallah, M.J.: The hiding virtues of ambiguity: Quantifiably resilient watermarking of natural language text through synonym substitutions. In: Proceedings of the 8th Workshop on Multimedia and Security. pp. 164–174. Association for Computing Machinery, New York, NY, US (2006). https://doi.org/10.1145/1161366.1161397

[29] Xue, T., Lau, F.C.M.: Concatenated synchronization error correcting code with designed markers. In: 2019 IEEE 5th International Conference on Computer and Communications (ICCC). pp. 1371–1376. IEEE, Piscataway, NJ, US (2019). https://doi.org/10.1109/ICCC47050.2019.9064318