

Covering Codes for Insertions and Deletions

Andreas Lenz, Cyrus Rashitchian, Paul H. Siegel, and Eitan Yaakobi

Abstract—A covering code is a set of codewords with the property that the union of balls, suitably defined, around these codewords covers an entire space. Generally, the goal is to find the covering code with the minimum size codebook. While most prior work on covering codes has focused on the Hamming metric, we consider the problem of designing covering codes defined in terms of insertions and deletions. First, we provide new sphere-covering lower bounds on the minimum possible size of such codes. Then, we provide new existential upper bounds on the size of optimal covering codes for a single insertion or a single deletion that are tight up to a constant factor. Finally, we derive improved upper bounds for covering codes using $R \geq 2$ insertions or deletions. We prove that codes exist with density that is only a factor $O(R \log R)$ larger than the lower bounds for all fixed R . In particular, our upper bounds have an optimal dependence on the word length, and we achieve asymptotic density matching the best known bounds for Hamming distance covering codes.

Index Terms—covering codes, insertions and deletions.

I. INTRODUCTION

Covering codes are a core object of study in coding theory and discrete mathematics. They have found applications in diverse areas such as data compression [1], football pools [2], circuit complexity [3], lattice problems [4], and approximate nearest neighbor search [5]. Previous work has mostly studied covering codes with respect to substitutions (i.e., the Hamming distance). Recently, due to the large amount of textual and biological data, there has been a resurgence of interest in the Levenshtein distance and in channels with insertion and deletion errors (e.g., [6], [7], [8], [9], [10], [11], [12]). Despite this substantial progress, the Levenshtein distance remains poorly understood compared to other metrics on discrete spaces, and many fundamental questions remain open.

In this paper, we study covering codes for insertions and deletions. Loosely speaking, we aim to cover a space of words by the union of balls around a minimum number of codewords. Let Σ_q^n denote the set of length- n words over a q -ary alphabet. For the case of insertions and deletions, a codeword $c \in \Sigma_q^n$

covers a word y at radius R if y can be obtained from c by inserting, or respectively deleting, exactly R symbols. This means that the covering problem for insertions deals with finding a small set of words of length n such that each word of length $n + R$ is a supersequence of a codeword. Similarly, for the case of deletions, each word of length $n - R$ must be a subsequence of some codeword. In both cases, the codewords are the centers of balls with radius R under the Levenshtein distance. Notice, however, that the codewords and the covered words reside in different spaces because they have different lengths. Hence, the covering problem for insertions and deletions is inherently asymmetric.

Although there is a rich literature on covering codes for the Hamming distance [1], as well as recent improvements for insertion/deletion error-correcting codes (e.g., [13], [14], [15], [16], [17]), much less is known about covering codes using insertions or deletions. Two key challenges are the (ir)regularity of the balls and the asymmetry of the covering problem. Insertion balls are regular, in the sense that for any $x \in \Sigma_q^n$ and $R \geq 1$, there are exactly $\sum_{i=0}^{n+R} \binom{n+R}{i} (q-1)^i$ words of length $n + R$ obtainable by inserting R symbols into x (cf. [18]). In contrast, deletion balls are irregular, and their sizes depend on many properties of their center, such as the number of runs. In fact, a tractable exact formula remains unknown for the size of the deletion balls with radius three or greater. This irregularity and lack of an explicit formula for the ball size means that, compared to the Hamming distance, it is inherently more challenging to derive bounds on the minimum covering code size, even asymptotically.

In some cases, we can infer results on covering codes from the theory of error-correcting codes. This is due to the existence of *perfect* error-correcting codes, for which the balls of radius R around all codewords are not only distinct but also cover each word once. For example, the Varshamov-Tenengolts (VT) code is a perfect binary single-deletion-correcting code [19]. It is known that the VT code is the largest single-deletion-correcting code for $n \leq 14$ [20], and this is conjectured to be true for $n > 14$ (see Skoane [21, Conj. 2.6]). This conjecture however remains open. Nevertheless, since the VT code is indeed a perfect single-deletion-correcting code, it is also a single-deletion-covering code.

While it has been shown that an R -deletion-correcting code is equivalent to an R -insertion-and-deletion-correcting code [26], this property does not hold for the case of covering codes. This means that the VT codes are not single-insertion-covering codes and thus also not perfect codes for correcting a single insertion. In fact, it has been shown that the only perfect single-insertion-correcting codes are binary and have length two [19]. Therefore, the best possible size of a single-insertion-covering code is unknown, and constructing optimal covering codes in this case is a highly non-trivial problem,

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