PACMANN: Efficient Private Approximate Nearest Neighbor Search

Mingxun Zhou Elaine Shi Giulia Fanti

Carnegie Mellon University

Abstract

We propose a new private Approximate Nearest Neighbor (ANN) search scheme named PACMANN that allows a client to perform ANN search in a vector database without revealing the query vector to the server. Unlike prior constructions that run encrypted search on the server side, PACMANN carefully offloads limited computation and storage to the client, no longer requiring computationally-intensive cryptographic techniques. Specifically, clients run a graph-based ANN search, where in each hop on the graph, the client privately retrieves local graph information from the server. To make this efficient, we combine two ideas: (1) we adapt a leading graph-based ANN search algorithm to be compatible with private information retrieval (PIR) for subgraph retrieval; (2) we use a recent class of PIR schemes that trade offline preprocessing for online computational efficiency. PACMANN achieves significantly better search quality than the state-of-the-art private ANN search schemes, showing up to 2.5× better search accuracy on real-world datasets than prior work and reaching 90% quality of a state-of-the-art non-private ANN algorithm. Moreover on large datasets with up to 100 million vectors, PACMANN shows better scalability than prior private ANN schemes with up to 2.6× reduction in computation time and 1.3× reduction in overall latency.

1 Introduction

Today, most search systems require clients to send a plaintext query to the server, which performs a search over the database and returns the most relevant document(s). This architecture poses a serious privacy risk to users, whose search queries can leak privacy-sensitive information [aol06]. To this end, an important problem is that of *private search*: algorithms that allow a user to search a database without revealing their query to the server in plaintext. To date, there have been several proposed private search algorithms, which provide cryptographic privacy guarantees over the user's query [HDCG+23, ABG+24, SSLD22].[1] However, **existing algorithms suffer from poor tradeoffs between: (1) search quality and/or (2) efficiency.** For example, consider Tiptoe [HDCG+23], the state-of-the-art private search algorithm with cryptographically strong privacy guarantees. Tiptoe incurs a linear computation cost for the server per query; that is, the server needs to at least scan through the entire database for each query. Although Tiptoe is parallelizable, the linear computation cost may be a bottleneck for large-scale applications. At the same time, Tiptoe's search accuracy is limited. For example, it only achieves around 40% of the non-private search accuracy in the MS-MARCO dataset.

Typical private search algorithms can be categorized by two main design choices: the search algorithm and the privacy primitive. These two are closely intertwined: the search algorithm must be chosen to be compatible with the privacy primitive, while also ensuring that information is not leaked to the server and the search quality is not overly degraded. For example, Tiptoe makes

[1] Cryptographic privacy means that the server learns cryptographically negligible information about the query.

two design choices that limit its performance: (1) It uses a clustering-based approximate nearest neighbor (ANN) algorithm that significantly limits the search quality. (2) Its privacy guarantees are based on a preprocessed somewhat homomorphic encryption (SHE) scheme, which requires significant computation linear in the dataset size.

Given the status quo, we ask the following question:

Can we design a private search algorithm that achieves high search quality with low latency?

1.1 Our Contribution

In this work, we present PACMANN (Privately ACcess More Approximate Nearest Neighbors), a fully private nearest neighbor search algorithm that addresses the search quality-efficiency tradeoff. We made the observation that the existing private search solutions fail to leverage the graph-based ANN search algorithms [MY18, JSDS+19, IM18] that have shown better quality-efficiency tradeoffs compared to other families of ANN search algorithms (including Local-Sensitive Hashing (LSH) [IM98, SSLD22] and clustering-based algorithms [ABG+24, HDCG+23]). The core challenge lies in the fact that graph-based ANN search algorithms are inherently *iterative* algorithms that require multiple adaptive steps to find the results (See Figure 3). Implementing such algorithms with generic privacy-preserving techniques like fully homomorphic encryption (FHE) [Gen09a] or secure multi-party computation (SMPC) [CD+15a] could incur high overheads.

Our key insight is that we can implement a graph-based ANN search algorithm by running the iterative search locally on the client side, so that the computation can be done in plaintext and with no privacy concern. To achieve this without the client storing the whole graph structure, we let the server store the graph structure and let the client dynamically fetch necessary information from the server. We need to further use a cryptographic primitive named Private Information Retrieval (PIR) to allow the client to retrieve the graph information from the server without revealing the access pattern to the server. However, if we apply standard PIR schemes [CGKS95] here, the computation per graph access will be at least linear to the size of the whole graph[2], making the whole system inefficient. We utilize a new sublinear PIR construction named Piano [ZPSZ24] from the recently popularized client-preprocessing PIR model [CK20] to address the efficiency issue. The Piano PIR scheme allows the client to privately query the graph information with sublinear computation and communication per-query cost after a one-time preprocessing phase with linear cost. Moreover, the preprocessing phase can be shared for multiple ANN queries (each ANN query makes mulitple accesses to the graph), so the preprocessing cost can be amortized. Finally, we have to make further customizations and optimizations to both the graph-based ANN search algorithm and the Piano PIR to make the whole scheme efficient.

Contributions. We summarize our contributions as follows:

1. **Algorithm Design.** We present the design of PACMANN, which builds on a customized graph-based ANN search algorithms and Piano PIR [ZPSZ24]. In graph-based ANN search algorithms [MY18, JSDS+19, IM18], each vertex in the graph represents a database vector and is connected to multiple other vertices based on proximity in a vector (embedding) space. Given a query vector, the algorithms usually start from a given vertex and traverse the graph to find ANNs. In each step of the traversal, the algorithms examine all connected vertices to the current vertex and move to the next vertex that is closer to the query, until a stopping criterion is met. To implement graph traversal algorithm privately, PACMANN requires the client to *locally* run graph traversal over carefully-selected subgraphs. To efficiently retrieve the appropriate

[2]The lower bound is proved in [BIM00].

subgraph, we modify an existing, practically-efficient PIR scheme [ZPSZ24] to handle batched queries. Figure 1 gives a high-level system overview of PACMANN.

2. **Empirical results.** We empirically evaluate the performance of PACMANN in terms of search quality, query latency, communication, and storage costs. Our results show that PACMANN achieves significantly better search quality than the clustering-based private ANN search algorithm used by state-of-the-art Tiptoe [HDCG+23] and Wally [ABG+24]. For example, our implementation finds the most relevant result in around 63% of the queries on the MSMARCO dataset, compared to 29% for clustering-based algorithms—a **2.1x improvement** in search success rate. In the 100M SIFT dataset, our evaluation shows a **2.5x better** recall@10 compared to Tiptoe. Figure 2 shows that PACMANN achieves 90% of the search quality of the leading non-private ANN algorithm (NGT [IM18]), measured in mean reciprocal ranking (MRR) and recall. PACMANN also has lower latency than linear computation cost algorithms, including Tiptoe [HDCG+23] and Preco [SSLD22] when the database is larger than 5M records in the LAN setting (i.e., when the search engine and the database are co-located, so network round-trip latency is 5 ms), and 50M records in the WAN setting, respectively. For example, for a database with 100M records, Tiptoe requires at least 4s of search latency, whereas PACMANN achieves 1.6s in the LAN setting **(a 60% reduction)** and 3.1s in the WAN setting **(a 22% reduction)**. Experimental details can be found in Section 4 and Appendix D.

1.2 Related Work

Private Information Retrieval (PIR) [CGKS95, CG97, CMS99, Cha04, GR05] is a cryptographic primitive that allows a user to retrieve information from a public database without revealing the query to the service provider. On the practical side, most recent works that rely on Homomorphic Encryption [MBFK16, AYA+21, MW22, HHCG+22] construct communication-efficient PIR schemes with linear computation cost per query, resulting in large query latency for large databases. To achieve sublinear computation cost per query, the "client-preprocessing PIR" model [CK20, SACM21, CHK22, ZLTS23, LP22] introduces a preprocessing phase that allows the client to store sketched information about the database. Early theoretical works already showed that this model can indeed

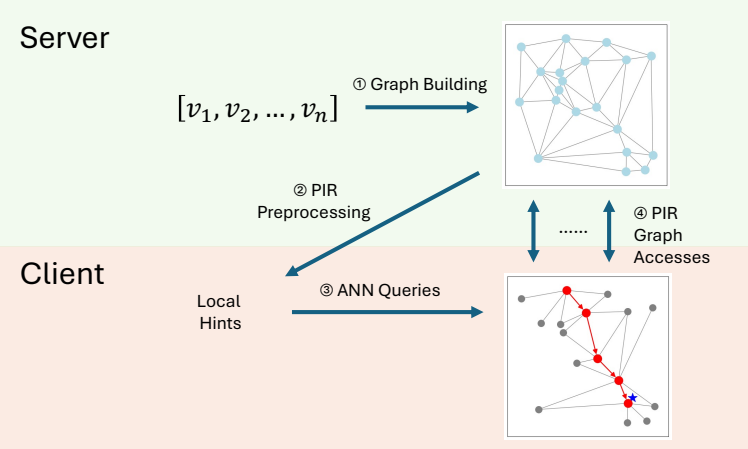
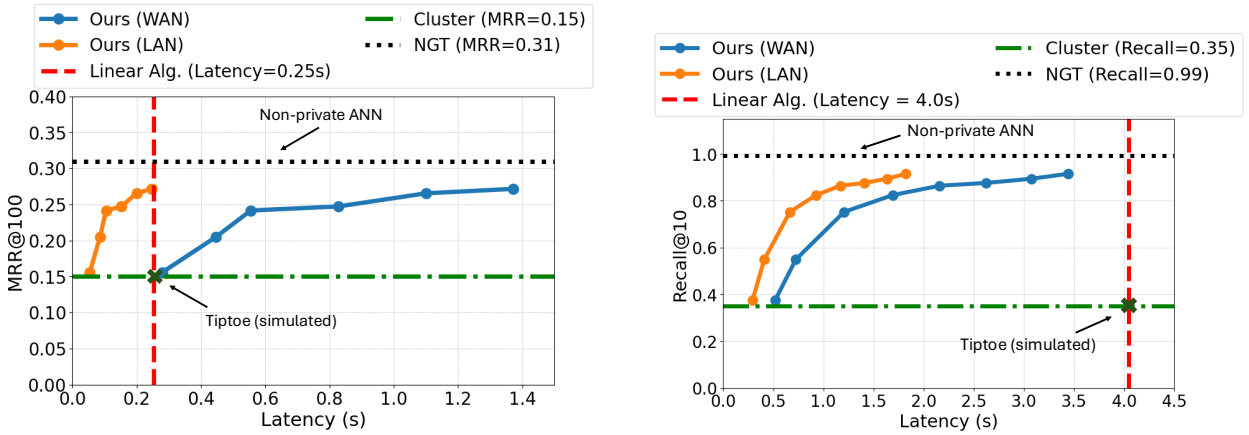


Figure 1: The high-level overview of PACMANN. 1) The server builds a graph structure on the database vectors. 2) The client and the server run the preprocessing protocol for the PIR scheme, storing the local hint in client's storage. 3) The client makes ANN queries. 4) The client runs the graph traversal algorithm locally, but uses the PIR scheme to access the graph information remotely.



(a) Results on MS-MARCO dataset.

(b) Results on SIFT-100M dataset.

Figure 2: Tradeoff between search quality and latency. "Linear Alg." is an SIMD-optimized linear algorithm that lower bounds the latency of Tiptoe [HDCG+23], the state-of-the-art private search algorithm. As a safe lower bound, we do not include network latency for "Linear Alg.". "Cluster" is a clustering-based algorithm that upper bounds the quality of Tiptoe. The intersection of the two can be viewed as our (simulated) result for Tiptoe. We upper bound search quality with NGT, a state-of-the-art non-private ANN search algorithm [IM18]. We plot PACMANN result in both the LAN (5ms RTT) and WAN (50ms RTT) settings.

achieve sublinear (amortized) computation and communication cost per query. Towards concrete efficiency, Zhou et al. [ZPSZ24] and subsequent works [GZS24, MIR23, NGH24] introduce practically efficient preprocessing PIR schemes by making the following tradeoff: as long as the client can make a streaming pass over the database in the preprocessing phase (with linear downloading cost but sublinear storage cost), the PIR scheme can be constructed with minimal cryptographic assumptions (from one-way functions) and can achieve the best known online query efficiency among all known PIR schemes – taking only 10-100 milliseconds and a few kilobytes of communication cost per query to a database with billions of records.

Most Private Information Retrieval (PIR) schemes are designed for the basic array-type access where the client knows exactly the location of the record to query. There are some other works that consider more advanced access pattern like key-value type of queries [CGN97, PSY23, CD24]. However, ANN search usually requires a more sophisticated search algorithm and thus requires a more complex access pattern.

Several existing works directly consider the private search problem. In addition to Tiptoe [HDCG+23], Wally [ABG+24] improves the efficiency of Tiptoe by relaxing the privacy guarantee to differential privacy, and relying on a large batch of anonymous queries to hide the privacy of an individual query. Nonetheless, Tiptoe and Wally are based on a simple clustering-based algorithm that partitions the vectors into roughly $\sqrt{n}$ clusters, and only performs exhaustive search in one particular cluster during the search phase. This simple algorithm is not competitive with the state-of-the-art non-private ANN search algorithms. For example, when we evaluate this algorithm on the MSMARCO dataset, its success rate to find the most relevant result is less than 30%, while a non-private ANN search algorithm can have 75% of success rate or even higher. Preco [SSLD22] is another cryptographically private ANN search algorithm that utilizes a Locality Sensitive Hashing (LSH) based search algorithm. Unfortuantely, Preco makes a strong assumption that there must be two non-colluding servers to store the database, which is not applicable in many practical scenarios.

Preco also requires a linear computation cost on both servers per query.

In an independent and concurrent work, Zhu et al.[ZPZP24] also proposes a privacy-preserving ANN search algorithm under a different setting such that the database is provided by the client and outsourced to the server while being encrypted. In that case, the server not only stores the per-client encrypted database, but can also store per-client state to facilitate the search. Their solution is based on the HNSW graph-based ANN indexing algorithm [MY18] and Path Oblivious RAM (ORAM) [SvDS+18]. Our setting is different that we assume the database is public and shared among all clients, while the server does not have any per-client storage.

2 Our Graph-based ANN Construction

As a starting point, we describe our ANN search algorithm construction without privacy considerations. Our construction relies on a customized version of the graph-based ANN search algorithm.

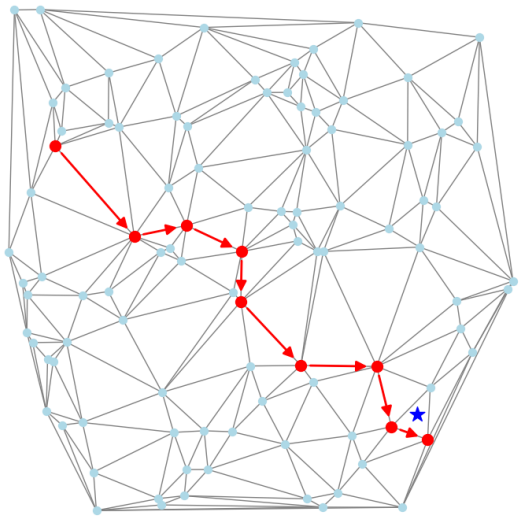


Figure 3: An illustration of the graph-based ANN search algorithm on a 2D space. The starting vertex is located around the upper left part of the graph, and the query vector is shown as a blue star. We highlight the path that the algorithm takes to reach the approximate nearest neighbor.

2.1 Preliminary: Generic Graph-based ANN Search Blueprint

Many popular graph-based ANN search algorithms such as NSW [MPLK12], HNSW [MY18], DiskANN [JSDS+19], NGT [IM18], and FINGER [CCJ+23] follow the same technical blueprint: the algorithm builds a graph based on the input vectors during the preprocessing phase, and then performs a graph traversal algorithm to find the approximate nearest neighbors for a given query vector. We provide a graphical illustration of this process in Figure 3 and a pseudocode description in Figure 4.

Preprocessing. The preprocessing phase takes in n vectors $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d \times n}$ from a metric space and builds an indexing graph G where the n vertices represent the vectors. Different

algorithms may have different ways of selecting graph edges. One common approach (e.g., seen in [JSDS+19]) is to connect each vertex v_i to several nearest neighbors, i.e. vectors that are close to v_i in the metric space, as well as multiple distant neighbors to ensure the diversity of the neighbor list [WXYW21]. Most recent ANN algorithms use more advanced structures on top of the indexing graph (e.g. hierarchical structure in HNSW [MY18] or auxiliary tree-structure in NGT [IM18]) to improve the search efficiency.

Query. Given a query vector q, the query algorithm performs a graph traversal algorithm on the index graph G and outputs a vertex u^* as the approximate nearest neighbor of q. The search algorithm starts from an entry point u_{start}, often picked as the closest vertex to the centroid of DB. We denote the set of neighbors of a node v as $N(v)$. In each hop, the search algorithm greedily moves from the current vertex v to its neighbor in $N(v)$ that is the closest to the query vector q. The algorithm terminates when the number of hops reaches a certain threshold or a local minimum is met, i.e. none of the neighbors is closer to q than the current iterate. This can be easily extended to outputing K approximate nearest neighbors by keeping track of the visited vertices and outputting the top K nearest vertices in the visited set.

2.2 Our Customized Graph Building Algorithm

To make graph-based ANN search private, Pacmann imposes two constraints: (1) We retain the single graph structure, as opposed to adding auxiliary structures, as is done in the non-private setting. This is done to facilitate the upgrade to the privacy-preserving version. (2) We enforce regularity on the graph's out-degree distribution. This prevents information leakage from the number of neighbors accessed. These properties are not met by existing ANN algorithms, and we customize the graph-building algorithm to meet them. We describe the high-level idea to build a regular C-out directed indexing graph here and defer the formal description to Appendix B.

Start from an unbalanced graph. Our first observation is that we can take advantage of existing ANN libraries to find nearby neighbors for all vectors in the database and treat them as the candidate neighbors in the graph. Specifically, we find $2C$ approximate nearest neighbors as neighbor candidates for each vertex using an existing ANN library (e.g., NGT [IM18]), then trim the candidate list to C candidates with the sparse-neighborhood-graph (SNG) heuristic [AM93]. Roughly, SNG sorts the candidates by their distance to the vertex and adds candidates to the neighbor list one by one. It only adds a candidate if it is not too close to a neighbor already in the list; this is done to ensure diversity (see Figure 7 for the details). We temporarily add directed edges between each vertex and its C neighbor candidates *in both directions* to ensure the graph is well-connected, i.e. so that each vertex has at least C inbound and C outbound directed edges.

Balancing the graph. We now have a graph that could be highly unbalanced in terms of the degrees. We use a sampling technique to balance the graph. That is, for each directed edge $(x \to y)$, we keep it with a probability of $C/\mathsf{InboundDegree}(y)$. This ensures that a vertex will have C inbound endges in expectation after the sampling process. Then, we ensure that each vertex has exactly C outbound edges. For those vertices with more than C outbound edges, we again use the SNG heuristic to trim the outbounds to C. For those vertices with fewer than C outbound edges, we connect them to vertices selected uniformly at random.

3 Pacmann: Private Graph-based ANN

We next describe how Pacmann protects query privacy over our customized graph-based ANN search algorithm in Section 2. We start with a basic, inefficient construction, then show how

Figure 4: Description of the graph based ANN search algorithm including the optional optimizations. The pseudocode can be read in the following two ways: 1) the non-highlighted part describes the generic graph-based ANN search algorithm; 2) the full description, including the optimizations we introduced in Section 3.3, describes our customized version of the algorithm. In the non-private setting, the algorithm is run in the server. In the private setting, the client will run the query algorithm locally, and use Batched Piano PIR to perform the information retrieval dynamically and privately.

Graph-based ANN Search Algorithm

Preprocessing.

- Input: a set of n vectors $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d \times n}$.
- Output: a directed graph G with n vertices corresponding to the n vectors in DB, and an entry point(s) u_{start}, $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$.

1. $G \leftarrow \mathsf{ANN.BuildGraph}(\mathsf{DB})$; *// Description in Section 2.2*
2. Let the closest vector to the centroid be the starting vertex $u_{\text{start}} = \arg\min_{u \in [n]} \Delta(v_u, \frac{1}{n}\sum_{j \in [n]} v_j)$.
3. Let the extra starting vertices be $\sqrt{n}$ random vertices $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$ sampled from $[n]$.

Query.

- Parameters: max hop number H, beam search width m denoting the number of parallel paths to explore.
- Input: a query vector $q \in \mathbb{R}^d$.
- Output: an index u^* such that v_{u^*} is recognized as an approximate nearest neighbor of q.

1. Let $u = u_{\text{start}}$.
2. Let $u_1, \ldots, u_m$ be the top m vertices in $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$ that are closest to q.
3. For $t = 1, 2, \ldots, H$:
   - Update u as following:
     - Read the neighbor list $N(u)$ from G and all vectors v_j for $j \in N(u)$ from DB.
     - Let $u' = \arg\min_{j \in N(u)} \Delta(v_j, q)$.
     - If $\Delta(u', q) \leq \Delta(u, q)$, update $u \leftarrow u'$.
   - Similarly, update $u_1, \ldots, u_m$.
4. Let $u = \arg\min_{u' \in \{u, u_1, \ldots, u_{\sqrt{n}}\}} \Delta(u', q)$.
5. Output $u^* = u$.

Pacmann optimizes it. Due to space constraints, we present the full construction of Pacmann in Appendix C.

3.1 Inefficient Private Graph-based ANN Search with Classical PIR

As a strawman scheme, one could try to protect query privacy by implementing the search algorithm with generic cryptographic primitives, such as fully homomorphic encryption [Gen09b]. and/or multi-party computation [CD+15b]. However, the search algorithm of graph-based ANN is inherently iterative and adaptive that during the graph traversal process, each hop's vertex is dynamically determined by both the previous hop's vertex and also the query vector. Handling such (adaptive) iteration is a common challenge in designing cryptographic protocols [3] as observed by previous works [BFK+09, DdSGOTV22, CGG+24, GHAHJ22, HKP21]

Localized Searching. Our main idea is to *perform the iterative graph traversal algorithm on the client side*, completely removing the privacy concern of performing iterative computation on the server. Naively, this would require the client to store the whole indexing graph, which is impractical in terms of storage cost. Instead, we let the client dynamically and privately retrieve subgraph information from the server. Specifically, during search, the client can retrieve the neighbor list $N(v_i)$ of the current vertex v_i and also all vectors in the neighbor list from the server for each hop. The client then computes the distances between the query vector q and all the neighbor vectors in $N(v_i)$ locally, and chooses the closest neighbor within that set. This process is repeated until the search terminates.

Protecting Retrieval Privacy with PIR. Even without directly observing the query vector, the server can infer non-trivial information from the vertex indices retrieved by the client. For example, if the server learns that the client retrieves many vertices whose underlying records represent documents about food topics, the server can infer that the client is searching for information about foods. Thus, the final challenge is how the client can retrieve the graph information (including the neighbor lists and the vectors) without revealing which vertex it is retrieving.

We use a Private Information Retrieval (PIR) scheme for this purpose. Standard PIR [CGKS95] allows a client to retrieve one or multiple entries from a server-stored database of n entries without revealing the indices of the entries to the server. To integrate a PIR scheme into our private graph-based ANN search algorithm, we can run a standard PIR protocol for a database storing all the vertex information in the graph, where each entry i stores the vector v_i and also the neighbor list $N(i)$. Whenever the clients need to access the graph, it issues a PIR query to retrieve the information privately. Notice that by merging the vector information and also the neighbor information into a single database, we can finish each hop in one round of communication.

Efficiency Issue. This construction runs into a major efficiency issue. It was formally proved by Beimel, Ishai, and Malkin [BIM00] that any PIR scheme requires $\Omega(n)$ computation cost if there is no preprocessing, and if the server stores the database naively without encoding. Hence, if we have a non-private graph-based ANN algorithm that proceeds for H hops, and each hop requires the client to retrieve the information of C neighbors, the online computation cost of the scheme will be $\Omega(HCn)$, which is super-linear in n. This is worse than the prior linear-cost private ANN schemes [HDCG+23, SSLD22].

[3] The standard FHE or MPC techniques are designed for the so-called circuit model, where the computation flow is fixed and known in advance. Although the circuit model is indeed Turing-complete, it does not naturally support a random-access memory and control flow operations like if-else conditions. In the context of graph-based ANN search, we do need to (adaptively) read the graph from a random access memory, so the standard techniques are not directly applicable.

3.2 Improving Efficiency with Preprocessing PIR

To address this efficiency limitation, we utilize a new paradigm of PIR schemes: client-side preprocessing PIR [CK20]. Unlike standard PIR, client-side preprocessing PIR achieves sublinear (amortized) query cost by allowing an one-time preprocessing phase before the query phase in which the client will eventually store some useful information about the database. Specifically, we use a recent PIR scheme called Piano [ZPSZ24] that achieves practical efficiency for the single-server setting, matching our requirements. Given a database with n entries, Piano achieves $\tilde{O}(\sqrt{n})$ computation and communication per query[4] with $\tilde{O}(\sqrt{n})$ client storage after an one-time preprocessing phase that incurs linear computation and communication costs. We provide a review on Piano PIR in Appendix C.1. Other alternatives of single-server PIRs [GZS24, MIR23, WLZ+23] could also be used in our construction for similar efficiency guarantees.

By applying Piano PIR scheme to our private ANN construction, after a linear cost preprocessing phase, each PIR query in the graph traversal algorithm will incur $\tilde{O}(\sqrt{n})$ computation and communication cost. Again, if we assume the search algorithm takes H hops and each hop requires the client to retrieve the information of C neighbors, the overall running time of the scheme will be $\tilde{O}(HC\sqrt{n})$. As long as $H \cdot C$ is $o(\sqrt{n})$, the resulting scheme will have sublinear computation cost, being more effcient than the prior private ANN schemes [HDCG+23, SSLD22].

Tradeoff and Practicality of Preprocessing Despite significant online efficiency improvements, the Piano PIR client must download the whole database (i.e., the indexing graph) in a streaming fashion during the preprocessing phase. Here, streaming means that the client only stores a small portion of the database to preprocess at a time, but the total amount of data the client has to download is still the whole database. Therefore, our scheme is more suitable for a client with good network connection. In our evaluation where we assume a good network connection (1 Gbps), the preprocessing phase takes around 5 minutes and 3 GB of client storage space for a database with 100 million vectors, and the total download communication is around 60GB. An alternative approach to reduce the preprocessing cost is to have a second server to preprocess the database and directly provide the client with the preprocessed results, as suggested in many existing PIR schemes [ZPSZ24, LP23, GZS24, KCG21].

3.3 Necessary Optimizations

In practice, we observe that the total number of visited vertices in the graph-based search algorithm (that is, the product between max hop number H and the graph out-degree C) tends to be around a few hundreds or thousands. We describe the necessary optimizations here and conduct an ablation study in the evaluation section to show the effectiveness these optimizations in Section 4. Empirically, we observe that our optimizations reduces the concrete computation cost by 76%, and the overall latency by nearly 70% (including the communication time).

Beam search. The basic description of the graph-based ANN search algorithm Figure 4 traverses the graph in a single path. In practice, we can explore m multiple paths in parallel. This approach is used in other graph-based ANN algorithms [JSDS+19]. Although doing so increases the query cost per hop, we observe that beam search significantly reduces the total hops to reach a given search quality, and is thus essential to reducing the overall latency.

Fast Starting. Intuitively, if the starting vertex is already very close to the query vector q, we can reach the approximate nearest neighbors with fewer hops. With fast starting, we let the client store around $O(\sqrt{n})$ vertices' information locally, and scan all these vertices to find those that are

[4]We use $\tilde{O}()$ to hide polylogarithmic factors.

already close to q to start the searching algorithm. We get this benefit for free, because Piano PIR already requires the client to store $\tilde{O}(\sqrt{n})$ vectors locally, which are selected uniformly at random.

Batched PIR Query. We observe that the PIR queries in each hop are parallel and can be handled in a single batch. We can use a batching technique called partial batch retrieval (PBR) [SSLD22] to further improve the efficiency. In PBR, we can use a pseudorandom permutation to permute the database upfront, and then partition the permuted database into B sub-databases where each sub-databases has n/B entries. On average, each sub-databases will have Q/B queries given a batch of Q queries (if we are using beam search, $Q = mC$). By doing this, each PIR query will be issued to a sub-database of size n/B instead of the full database, saving the computation and communication cost. To ensure privacy, the client has to issue a fixed number of queries for each sub-database, say choosing the number $T = 1.5Q/B$. If fewer than T queries are in the same sub-database, the client submits dummy queries. If more than T queries are in the same sub-database, the client only submits the first T queries and discards the rest. For example, if we have a batch size $Q = 32$ and set partition number $B = 16$ and $T = 3$, around 90% of the queries in the batch will be successfully submitted in expectation. [5]. Intuitively, if each vertex has 32 neighbors, our retrieval process can retrieve nearly 30 neighbors' information with a single batched query. Since the graph tends to be highly-connected, we observe that even with a mild query failure probability, the algorithm still finds good results with more hops.

Assume we are using the Piano PIR scheme that has $O(\sqrt{n})$ computation/communication cost per query. If we split the database into B sub-databases, the total cost for a Q-size batch will be $O\left(\left(\frac{Q}{B} + B\right) \cdot \sqrt{\frac{n}{B}}\right)$. The optimal selection will be $B = \Theta(Q)$ and the cost will be $O(\sqrt{Qn})$. This gives us a $O(\sqrt{Q})$ improvement in the efficiency compared to naively issueing Q independent queries that has $O(\sqrt{n}Q)$ cost.

4 Evaluation

We evaluate PACMANN's performance in terms of search quality and latency and compare it against two baselines: a state-of-the-art private ANN search algorithm, Tiptoe [HDCG+23], and a non-private ANN search algorithm, NGT [IM18]. Our evaluation results show that PACMANN achieves better search quality with lower online query latency than Tiptoe in two real datasets, SIFT and MS-MARCO. We provide more details in Appendix D, including a detailed breakdown of the preprocessing, storage and communication cost, and a discussion about quantization and the alternative implementations.

4.1 Evaluation Setup

Our open-source implementation[6] uses Python for data preprocessing and Golang for the core algorithm, including the graph ANN algorithm and the PIR scheme. Details of the implementation are provided in Appendix D. The experiments are run on a single server with a 2.4GHz Intel Xeon E5-2680 CPU and a 256 GB RAM. We evaluate the latency numbers on two simulated network

[5] We can approximate this process with randomly throwing Q balls into B bins, each with a maximum load of T, and calculate how many balls are discarded due to overflow in expectation. Given some fixed order of throwing the balls, the probability that the i-th thrown ball is thrown into a fully-loaded bin is always $\Pr[\mathsf{Bin}(i-1, 1/B) \geq T]$. Here, $\mathsf{Bin}(t, p)$ denotes the Binomial distribution – that is, the number of successful trials in t repeated, independent trials where each trial has success probability of p. Then, the expected number of discarded balls (i.e., failed queries) in total is $\sum_{i=1}^{Q} \Pr[\mathsf{Bin}(i-1, 1/B) \geq T]$.

[6] https://github.com/privsearch/private-search-temp

setting, the local area network (LAN) setting with 5ms round-trip-time (RTT) and the wide area network (WAN) setting with 50ms RTT. Although our implementation supports multi-threading optimization, we only use a single thread for all the experiments for a fair comparison.

Quality Metrics

Recall: Recall is the standard metric used in evaluating the quality of ANN algorithms [ABF20]. For each query q, if the algorithm outputs a K-index set I, and the top K ground truth is I^*, the recall@K is defined as: $\mathsf{Recall@}K = \frac{|I^* \cap I|}{K}$.

Mean Reciprocal Rank (MRR): MRR is a standard quality metric for information retrieval systems [NRS+16]. Given a query q, assume there is a ground truth index i^* such that $\mathsf{DB}[i^*]$ is the most relevant entry. If the client outputs a list of indices that actually contains i^* at the j-th rank where $j \leq K$, the reciprocal rank (denoted as RR@K) score is $1/j$. Otherwise, RR@K is 0. MRR is defined as the average of RR@K over multiple queries.

Datasets

SIFT Dataset [JTDA11] We use the first 100 million 128-dimensional vectors from the SIFT dataset for our evaluation. We vary the database size by picking the first 2 to 100 million vectors. We test 1,000 top-10 queries in the SIFT query set for each configuration, and measure the average recall@10 (the top-10 ground truth nearest neighbors for each query are provided by the dataset).

MS-MARCO Dataset. [NRS+16] The dataset contains 3.2 million text documents with more than 5000 test queries such that the top 1 relevant document is provided. We follow the same procedure as in the Tiptoe paper [HDCG+23] to process the dataset: 1) embed the documents and the queries into a 768-dimensional vector space with sentence-BERT [RG19]; 2) reduce the dimensions to 192 with PCA. We follow the same quality evaluation metric as in the Tiptoe paper that we compute the average MRR@100 for the first 1000 queries,

Baselines

- *Tiptoe (Simulated).* We aim to compare our scheme against the state-of-the-art private ANN search algorithm, Tiptoe [HDCG+23]. Due to resource constraints, we were unable to run the full Tiptoe system, where the dominating cost comes from the clustering step that requires dozens of servers running hundreds of core-hours as reported in the original paper. Hence, we have simulated Tiptoe by using two baselines as follows.

  - Latency lower bound: *Linear Algorithm.* The Tiptoe algorithm computes n inner products per query with preprocessed homomorphic encryption. As a latency lower bound [7] we implement a linear time algorithm algorithm that just computes the inner product between the query and each database vector in plaintext. We optimized the implementation using AVX-512 instructions. The throughput of this algorithm is around 11.9 GB/s, matching the memory bandwidth of the machine. Finally, we do not include network latency for this baseline.
  - Quality upper bound: *Cluster.* We replicate the clustering-based ranking algorithm used in Tiptoe with full precision (32-bit)[8]. We cluster the vectors to $\sqrt{n}$ clusters offline. For each query, we find the closest cluster centroid, and search the nearest neighbor within the cluster.

[7] We compared the simulated online latency with the actual numbers reported in the original paper [HDCG+23], and the simulated latency is 8% less than the reported latency. See the detailed results in Appendix D.

[8] Our reimplementation of the clustering-based algorithm reached 0.15 MRR@100 on the MS-MARCO dataset, which is better than the 0.13 MRR@100 reported in the Tiptoe paper [HDCG+23].

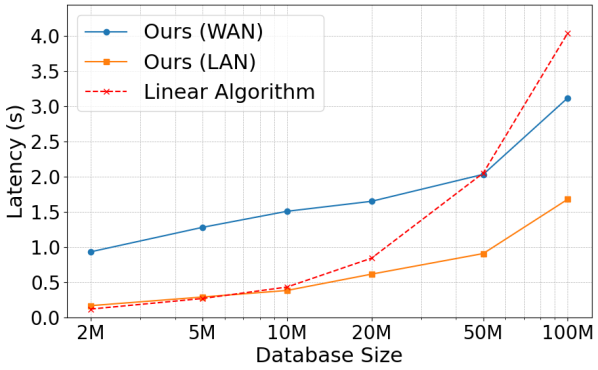


Figure 5: Latency results on different database sizes, sampled from the SIFT dataset. We tune the parameters of our scheme to achieve 0.90 recall@10 for each data point. For each data point, the total latency is the sum of the actual computation time and the round-trip time of the communication, mulitplied by the number of rounds. We plot both the LAN setting (5ms rtt) and the WAN setting results (50ms rtt) in this figure.

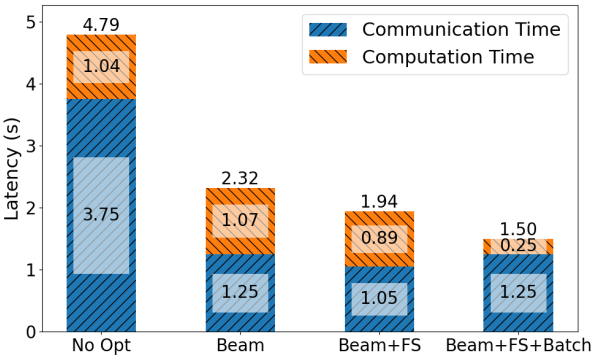


Figure 6: Ablation study on the 10M subset of SIFT (WAN setting). Given a fixed configuration, we increase the max number of rounds until the quality reaches 0.90 recall@10. "No Opt" means no optimizations are enabled. "Beam" means the beam search optimization. "FS" means the fast starting strategy. "Batch" means we enable the batch-mode Piano PIR. Our full implementation enables all the optimizations.

- *NGT.* NGT is one of the state-of-the-art non-private ANN search algorithms and we use the implementation from the GoNGT library [IM18]. We compare our scheme against NGT in terms of search quality.

4.2 Evaluation Results

Pacmann provides a favorable tradeoff between privacy, search quality, and latency. We first measure the tradeoff between search quality and query latency. Specifically, by increasing the number of rounds and number of parallel queries in each round, our algorithm can achieve higher search qualities at the cost of higher latency. The results are shown in Figure 2. We consider a wide range of search quality requirements, where the lower bound is set by the cluster search algorithm (replicating the Tiptoe search algorithm), and the upper bound is set by the non-private ANN algorithm, NGT. We observe that our scheme provides a wide range of tradeoff between quality and latency, and can indeed achieve within $\sim 90\%$ of NGT's search quality. In the SIFT-100M dataset, the advantage of our scheme is more significant, and even with 91% recall@10, our scheme still has a lower latency than the linear algorithm baseline.

Scalability: Pacmann outperforms Tiptoe in latency and accuracy on datasets of at least 2-50M records. We next evaluate the scalability of our scheme by scaling the database size up to 100 million vectors. We tune the parameters of our scheme to achieve 0.90 recall@10 for each data point; that is, 9 out of 10 of the search results are indeed the ground truth top-10 nearest neighbors on average. The results are shown in Figure 5. We observe that in the LAN setting where the computation time is dominant, our scheme beats the linear algorithm baseline when the database size is larger than 5M. In the WAN setting where the communication time is more dominant, our scheme beats the linear baseline when the database size is larger than 50M. We observe that the number of rounds to achieve a certain recall@10 grows roughly logarithmically

with the database size, and we know from the theoretical analysis that PIR cost scales with $\sqrt{n}$. This suggests that the total latency of our scheme grows sublinearly with the database size.

Ablation study: Our optimizations give a 70% latency reduction. Finally, we conduct an ablation study on the 10M subset of the SIFT dataset to evaluate the optimizations in Section 3.3: 1) *Beam Search:* The number of parallel paths in the beam search algorithm is increased from 1 to 3. 2) *Fast Starting:* The client starts the search by choosing the starting vertices from $\widetilde{O}(\sqrt{n})$ preprocessed vertices. 3) *Batched PIR:* We enable the batch-mode PIR for each round of the search.

We compare four configurations in Figure 6 where we increase the number of rounds until the quality reaches 0.90 recall@10. The beam search optimization significantly reduces the maximum number of rounds needed to achieve the same quality by 3x. Adding the fast-start strategy furtuher reduces the required rounds by 20%. When we enable the batch-mode PIR, we observe that the computation time in each round is reduced by 4x, but as we mentioned in Section 3.3, we do introduce some query failures, which we need to balance with the slight increase of the number of rounds.

5 Conclusion

We present PACMANN, a new private ANN search scheme that allows clients to perform nearest neighbor search query over hundreds of millions of vectors while preserving the query's privacy. PACMANN achieves significantly better search quality compared to the state-of-the-art private ANN search schemes and has lower latency in large-scale datasets. PACMANN could potentially be applied to a wide range of information retrieval applications including conventional search and retrieval-augmented generation.

Limitations. PACMANN has several limitations, which may present opportunities for future work. First, it inherits the drawback of the single-server preprocessing PIR schemes and requires the client to download the whole indexing structure offline in a streaming manner. Therefore, PACMANN will not be suitable for the network-constrained scenarios. PACMANN also does not naturally support dynamic updates to the database. Handling dynamic updates in PIR has been a challenging open problem. Finally, PACMANN is designed under the assumption that the database is public, so we do not consider server-side privacy. We leave these questions as interesting future directions.

Acknowledgment

We thank Justin Zhang for his help for the evaluations.

References

[ABF20] Martin Aumüller, Erik Bernhardsson, and Alexander Faithfull. Ann-benchmarks: A benchmarking tool for approximate nearest neighbor algorithms. *Information Systems*, 87:101374, 2020.

[ABG+24] Hilal Asi, Fabian Boemer, Nicholas Genise, Muhammad Haris Mughees, Tabitha Ogilvie, Rehan Rishi, Guy N Rothblum, Kunal Talwar, Karl Tarbe, Ruiyu Zhu, et al. Scalable private search with wally. *arXiv preprint arXiv:2406.06761*, 2024.

[AM93] Sunil Arya and David M Mount. Approximate nearest neighbor queries in fixed dimensions. In *SODA*, volume 93, pages 271–280. Citeseer, 1993.

[aol06] AOL search data release reveals a great deal. http://www.usatoday.com/tech/columnist/andrewkantor/2006-08-17-aol-data_x.htm, 2006.

[AYA+21] Ishtiyaque Ahmad, Yuntian Yang, Divyakant Agrawal, Amr El Abbadi, and Trinabh Gupta. Addra: Metadata-private voice communication over fully untrusted infrastructure. In *15th USENIX Symposium on Operating Systems Design and Implementation, OSDI2021, July 14-16, 2021*, 2021.

[BDKP22] Shany Ben-David, Yael Tauman Kalai, and Omer Paneth. Verifiable private information retrieval. In *Theory of Cryptography Conference*, pages 3–32. Springer, 2022.

[BFK+09] Mauro Barni, Pierluigi Failla, Vladimir Kolesnikov, Riccardo Lazzeretti, Ahmad-Reza Sadeghi, and Thomas Schneider. Secure evaluation of private linear branching programs with medical applications. In *Computer Security–ESORICS 2009: 14th European Symposium on Research in Computer Security, Saint-Malo, France, September 21-23, 2009. Proceedings 14*, pages 424–439. Springer, 2009.

[BIM00] Amos Beimel, Yuval Ishai, and Tal Malkin. Reducing the servers computation in private information retrieval: Pir with preprocessing. In *CRYPTO*, pages 55–73, 2000.

[CCJ+23] Patrick Chen, Wei-Cheng Chang, Jyun-Yu Jiang, Hsiang-Fu Yu, Inderjit Dhillon, and Cho-Jui Hsieh. Finger: Fast inference for graph-based approximate nearest neighbor search. In *Proceedings of the ACM Web Conference 2023*, pages 3225–3235, 2023.

[CD+15a] Ronald Cramer, Ivan Bjerre Damgård, et al. *Secure multiparty computation*. Cambridge University Press, 2015.

[CD+15b] Ronald Cramer, Ivan Bjerre Damgård, et al. *Secure multiparty computation*. Cambridge University Press, 2015.

[CD24] Sofía Celi and Alex Davidson. Call me by my name: Simple, practical private information retrieval for keyword queries. *Cryptology ePrint Archive*, 2024.

[CG97] Benny Chor and Niv Gilboa. Computationally private information retrieval. In *STOC*, 1997.

[CGG+24] Arka Rai Choudhuri, Sanjam Garg, Aarushi Goel, Sruthi Sekar, and Rohit Sinha. Sublonk: Sublinear prover plonk. *Proceedings on Privacy Enhancing Technologies*, 2024.

[CGKS95] Benny Chor, Oded Goldreich, Eyal Kushilevitz, and Madhu Sudan. Private information retrieval. In *FOCS*, 1995.

[CGN97] Benny Chor, Niv Gilboa, and Moni Naor. Private information retrieval by keywords. 1997.

[Cha04] Yan-Cheng Chang. Single database private information retrieval with logarithmic communication. In *ACISP*, 2004.

[CHK22] Henry Corrigan-Gibbs, Alexandra Henzinger, and Dmitry Kogan. Single-server private information retrieval with sublinear amortized time. In *Eurocrypt*, 2022.

[CK20] Henry Corrigan-Gibbs and Dmitry Kogan. Private information retrieval with sublinear online time. In *EUROCRYPT*, 2020.

[CMS99] Christian Cachin, Silvio Micali, and Markus Stadler. Computationally private information retrieval with polylogarithmic communication. In *EUROCRYPT*, pages 402–414, 1999.

[DdSGOTV22] Cyprien Delpech de Saint Guilhem, Emmanuela Orsini, Titouan Tanguy, and Michiel Verbauwhede. Efficient proof of ram programs from any public-coin zero-knowledge system. In *International Conference on Security and Cryptography for Networks*, pages 615–638. Springer, 2022.

[DGM+24] Haya Diwan, Jinrui Gou, Cameron Musco, Christopher Musco, and Torsten Suel. Navigable graphs for high-dimensional nearest neighbor search: Constructions and limits. *arXiv preprint arXiv:2405.18680*, 2024.

[Gen09a] Craig Gentry. Fully homomorphic encryption using ideal lattices. In *Proceedings of the forty-first annual ACM symposium on Theory of computing*, pages 169–178, 2009.

[Gen09b] Craig Gentry. Fully homomorphic encryption using ideal lattices. In *Proceedings of the forty-first annual ACM symposium on Theory of computing*, pages 169–178, 2009.

[GHAHJ22] Aarushi Goel, Mathias Hall-Andersen, Aditya Hegde, and Abhishek Jain. Secure multiparty computation with free branching. In *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, pages 397–426. Springer, 2022.

[GR05] Craig Gentry and Zulfikar Ramzan. Single-database private information retrieval with constant communication rate. In *ICALP*, 2005.

[GZS24] Ashrujit Ghoshal, Mingxun Zhou, and Elaine Shi. Efficient pre-processing pir without public-key cryptography. In *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, pages 210–240. Springer, 2024.

[HDCG+23] Alexandra Henzinger, Emma Dauterman, Henry Corrigan-Gibbs, , and Nickolai Zeldovich. Private web search with Tiptoe. In *29th ACM Symposium on Operating Systems Principles (SOSP)*, Koblenz, Germany, October 2023.

[HHCG+22] Alexandra Henzinger, Matthew M. Hong, Henry Corrigan-Gibbs, Sarah Meiklejohn, and Vinod Vaikuntanathan. One server for the price of two: Simple and fast single-server private information retrieval. Cryptology ePrint Archive, Paper 2022/949, 2022. https://eprint.iacr.org/2022/949.

[HKP21] David Heath, Vladimir Kolesnikov, and Stanislav Peceny. Masked triples: Amortizing multiplication triples across conditionals. In *IACR International Conference on Public-Key Cryptography*, pages 319–348. Springer, 2021.

[IM98] Piotr Indyk and Rajeev Motwani. Approximate nearest neighbors: towards removing the curse of dimensionality. STOC '98. Association for Computing Machinery, 1998.

[IM18] Masajiro Iwasaki and Daisuke Miyazaki. Optimization of indexing based on k-nearest neighbor graph for proximity search in high-dimensional data. *arXiv preprint arXiv:1810.07355*, 2018.

[JSDS+19] Suhas Jayaram Subramanya, Fnu Devvrit, Harsha Vardhan Simhadri, Ravishankar Krishnawamy, and Rohan Kadekodi. Diskann: Fast accurate billion-point nearest neighbor search on a single node. *Advances in Neural Information Processing Systems*, 32, 2019.

[JTDA11] Hervé Jégou, Romain Tavenard, Matthijs Douze, and Laurent Amsaleg. Searching in one billion vectors: re-rank with source coding. In *2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 861–864. IEEE, 2011.

[KCG21] Dmitry Kogan and Henry Corrigan-Gibbs. Private blocklist lookups with checklist. In *30th USENIX Security Symposium (USENIX Security 21)*, pages 875–892. USENIX Association, August 2021.

[Laa18] Thijs Laarhoven. Graph-based time-space trade-offs for approximate near neighbors. In *34th International Symposium on Computational Geometry (SoCG 2018)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2018.

[LMWY20] Kasper Green Larsen, Tal Malkin, Omri Weinstein, and Kevin Yeo. Lower bounds for oblivious near-neighbor search. In *Proceedings of the Fourteenth Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 1116–1134. SIAM, 2020.

[LP22] Arthur Lazzaretti and Charalampos Papamanthou. Single server pir with sublinear amortized time and polylogarithmic bandwidth. Cryptology ePrint Archive, Paper 2022/830, 2022. https://eprint.iacr.org/2022/830.

[LP23] Arthur Lazzaretti and Charalampos Papamanthou. Treepir: Sublinear-time and polylog-bandwidth private information retrieval from ddh. In *CRYPTO*, 2023.

[MBFK16] Carlos Aguilar Melchor, Joris Barrier, Laurent Fousse, and Marc-Olivier Killijian. Xpir: Private information retrieval for everyone. *Proceedings on Privacy Enhancing Technologies*, pages 155–174, 2016.

[MIR23] Muhammad Haris Mughees, Sun I, and Ling Ren. Simple and practical amortized sublinear private information retrieval. Cryptology ePrint Archive, Paper 2023/1072, 2023.

[MPLK12] Yury Malkov, Alexander Ponomarenko, Andrey Logvinov, and Vladimir Krylov. Scalable distributed algorithm for approximate nearest neighbor search problem in high dimensional general metric spaces. In *Similarity Search and Applications: 5th International Conference, SISAP 2012, Toronto, ON, Canada, August 9-10, 2012. Proceedings 5*, pages 132–147. Springer, 2012.

[MW22] Samir Jordan Menon and David J. Wu. SPIRAL: Fast, high-rate single-server PIR via FHE composition. In *IEEE S&P*, 2022.

[MY18] Yu A Malkov and Dmitry A Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. *IEEE transactions on pattern analysis and machine intelligence*, 42(4):824–836, 2018.

[NGH24] Hoang-Dung Nguyen, Jorge Guajardo, and Thang Hoang. Client-efficient online-offline private information retrieval. Cryptology ePrint Archive, Paper 2024/719, 2024.

[NRS+16] Tri Nguyen, Mir Rosenberg, Xia Song, Jianfeng Gao, Saurabh Tiwary, Rangan Majumder, and Li Deng. Ms marco: A human-generated machine reading comprehension dataset. 2016.

[PS20] Liudmila Prokhorenkova and Aleksandr Shekhovtsov. Graph-based nearest neighbor search: From practice to theory. In *International Conference on Machine Learning*, pages 7803–7813. PMLR, 2020.

[PSY23] Sarvar Patel, Joon Young Seo, and Kevin Yeo. {Don't} be dense: Efficient keyword {PIR} for sparse databases. In *32nd USENIX Security Symposium (USENIX Security 23)*, pages 3853–3870, 2023.

[PY22] Giuseppe Persiano and Kevin Yeo. Limits of preprocessing for single-server PIR. In *SODA*, pages 2522–2548. SIAM, 2022.

[RG19] Nils Reimers and Iryna Gurevych. Sentence-BERT: Sentence embeddings using Siamese BERT-networks. In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, 2019.

[SACM21] Elaine Shi, Waqar Aqeel, Balakrishnan Chandrasekaran, and Bruce Maggs. Puncturable pseudorandom sets and private information retrieval with near-optimal online bandwidth and time. In *CRYPTO*, 2021.

[SSLD22] Sacha Servan-Schreiber, Simon Langowski, and Srinivas Devadas. Private approximate nearest neighbor search with sublinear communication. In *2022 IEEE Symposium on Security and Privacy (SP)*, pages 911–929. IEEE, 2022.

[SvDS+18] Emil Stefanov, Marten van Dijk, Elaine Shi, T.-H. Hubert Chan, Christopher W. Fletcher, Ling Ren, Xiangyao Yu, and Srinivas Devadas. Path ORAM: an extremely simple oblivious RAM protocol. *J. ACM*, 65(4):18:1–18:26, 2018.

[WLZ+23] Yinghao Wang, Xuanming Liu, Jiawen Zhang, Jian Liu, and Xiaohu Yang. Crust: Verifiable and efficient private information retrieval with sublinear online time. *Cryptology ePrint Archive*, 2023.

[WXYW21] Mengzhao Wang, Xiaoliang Xu, Qiang Yue, and Yuxiang Wang. A comprehensive survey and experimental comparison of graph-based approximate nearest neighbor search. *arXiv preprint arXiv:2101.12631*, 2021.

[ZLTS23] Mingxun Zhou, Wei-Kai Lin, Yiannis Tselekounis, and Elaine Shi. Optimal single-server private information retrieval. In *EUROCRYPT*, 2023.

[ZPSZ24] Mingxun Zhou, Andrew Park, Elaine Shi, and Wenting Zheng. Piano: Extremely simple, single-server pir with sublinear server computation. In *IEEE S& P*, 2024.

[ZPZP24] Jinhao Zhu, Liana Patel, Matei Zaharia, and Raluca Ada Popa. Compass: Encrypted semantic search with high accuracy. Cryptology ePrint Archive, Paper 2024/1255, 2024. https://eprint.iacr.org/2024/1255.

A Formal Definitions

K-Approximate Nearest Neighbor Search (K-ANN). Assume a d-dimensional metric space with a distance function $\Delta(\cdot,\cdot)$. Given a database containing n vectors, denoted as $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d\times n}$, and a query vector $q \in \mathbb{R}^d$ such that an K-approximate nearest neighbor search algorithm takes the database DB and the query vector q as input, and outputs an index set $I = \{i_1, \ldots, i_K\}$ such that the distances between q and $v_{i_1}, \ldots, v_{i_K}$ are minimized, i.e., $I = \{i_1, \ldots, i_K\}$ is an approximation to the true K-nearest neighbors of q in DB. Specifically, we use the recall or the mean reciprocal rank (MRR) to evaluate the quality of the approximation, depending on the context.

Single Server (Preprocessing) Private K-ANN. A single-server preprocessing private ANN protocol is run between a stateful client and a server. The protocol consists of two phases: preprocessing and queries.

1. **Preprocessing:** The preprocessing phase is run before the query phase and could involve the communication between the client and the server. The server will receive the vector database $\mathsf{DB} \in \mathbb{R}^{d\times n}$ as input.

2. **Queries:** The query phase can include multiple (adaptive) queries from the client. Each query is a vector $q \in \mathbb{R}^d$. The client and the server can have multiple rounds of communication for each query. And at the end, the client will output K indices where the corresponding vectors are the K-approximate nearest neighbors of q in DB.

Intuitively, the privacy of a private ANN protocol requires that the server learns negligible information about the query vector q. We will define the privacy of a private ANN protocol with a simulation-based definition. A single-server private ANN protocol satisfies privacy if there exists a simulator Sim such that for any probabilistic polynomial-time adversary $\mathcal{A}$ acting as the server, the views of $\mathcal{A}$ in the following two experiments are computationally indistinguishable:

- Real: the client interacts with $\mathcal{A}(1^\lambda, \mathsf{DB})$ who acts as the server. In each query step, $\mathcal{A}$ may adaptively choose the next query q for the client. The client is invoked with q as input.

- Ideal: the simulated client $\mathsf{Sim}(1^\lambda, n)$ interacts with $\mathcal{A}(1^\lambda, \mathsf{DB})$ who acts as the server and $\mathcal{A}$ still may adaptively choose the next query q for the client. However, the simulator is invoked with only the knowledge of the size of the database, and without the information of the chosen query q.

Throughout this paper, we assume the adversary is semi-honest [9].

B Details of Our Graph-based ANN Construction

We now provide a detailed description of our customized graph building algorithm in Figure 7.

C Detailed Construction Description

We include the full description of our algorithm in Figure 8. The algorithm further involves the local caching optimization that the client will keep track of all queried vertices and avoid repetitive queries.

[9] We could potentially the verifiable PIR techniques [BDKP22] to upgrade the security to malicious adversaries.

Our Graph Building Algorithm: ANN.BuildGraph.

Input: a set of n vectors $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d \times n}$ and a target degree C.

Output: a directed regular C-out graph G with n vertices corresponding to the n vectors in DB.

Subroutine: $\mathsf{ANN.TrimNeighbors}(u, L, C)$. *// Given a vertex u and a list of neighbors L, return the picked C neighbors of u in L with the SNG heuristic.*

1. Let w be the number of vertices in L and let $(i_1, \ldots, i_w)$ be the sorted indices in L according to the distance to the vector v_u (ascendingly).
2. Let $\mathsf{Kept} \leftarrow \emptyset$, $\mathsf{Dscd} \leftarrow \emptyset$.
3. For $j = i_1, \ldots, i_w$:
   (a) If $\exists j' \in \mathsf{Kept}$ such that $\Delta(v_j, v_{j'}) < \Delta(v_j, v_u)$, label j as discarded. *// SNG heuristic*
   (b) If j is not discarded, insert j to Kept. Otherwise, insert j to Dscd.
   (c) Terminate if $|\mathsf{Kept}| = C$.
4. If $|\mathsf{Kept}| < C$, insert the first $C - |\mathsf{Kept}|$ vertices in Dscd to Kept.
5. Return Kept.

Graph Building.

1. For each $u \in [n]$:
   (a) Let N_u be the set of $2C$ approximate neighbor indices to v_u obtained by an underlying ANN algorithm.
   (b) Trim N_u to C neighbors: let $N_u \leftarrow \mathsf{ANN.TrimNeighbor}(u, N_u, C)$.
   (c) For all $u' \in N(u)$, add directed edges $(u \to u')$ and edge $(u' \to u)$ to the graph G.
2. Fix $\mathsf{InDegree}(u)$ to be the in-degree of vertex u in the current graph G.
3. For each edge $(i, j) \in G$: keep the edge in G with probability $\frac{C}{\mathsf{InDegree}(j)}$.
4. For each $u \in [n]$:
   (a) Denote $N_G(u)$ be the set of outbounds of u in G.
   (b) If $|N_G(u)| < C$: add edges from u to random vertices in $[n]$ until $|N_G(u)| = C$.
   (c) If $|N_G(u)| > C$: let $N_G(u) \leftarrow \mathsf{ANN.TrimNeighbor}(u, N_G(u), C)$.
5. Output the graph G.

Figure 7: Description of our graph building algorithm ANN.BuildGraph.

C.1 Review on Piano PIR

We review the main idea of Pian PIR [ZPSZ24] below. During the preprocessing phase, the client will sample around $\sqrt{n}\log n$ random sets, each containing $\sqrt{n}$ random indices in $[n]$. For each sampled set S, the client will store the random seed to generate S, and also the sum of the entires indexed by S, denoted as $\mathsf{sum}(S) = \sum_{i\in S} \mathsf{DB}[i]$. The number of sets ensure the every entry in DB is included in at least one set. Then, for each query x, the client will first find a local set S that contains x. Since the client knows $\mathsf{sum}(S)$, if it can learn learn $\mathsf{sum}(S/\{x\})$, it can recover $\mathsf{DB}[x]$ by a simple subtraction. However, the client cannot query $\mathsf{sum}(S/\{x\})$ by directly sending those $\sqrt{n}-1$ indices to the server, because the server will notice that all the indices it received from the client are not x, which is a privacy issue. Piano fixes this issue by having the client remember roughly $\tilde{O}(\sqrt{n})$ random entries during the preprocessing phase, which are called the "replcaments". Then, instead of deleting x from S, the client will replace x with a replacement entry y and query the server of $\mathsf{sum}(S/\{x\}\cup\{y\})$ by sending all $\sqrt{n}$ indices in this "edited" set to the server. The server takes $\sqrt{n}$ computation to compute the sum and returns the result to the client. Since the client already knows the value of $\mathsf{DB}[y]$ in preprocessing, it can recover $\mathsf{DB}[x]$ by calculating $\mathsf{DB}[x] = \mathsf{sum}(S) - \mathsf{sum}\left(S/\{x\}\cup\{y\}\right) + \mathsf{DB}[y]$. It is not hard to see this single-query version of Piano is indeed private – the server only sees $\sqrt{n}$ random indices that are independent of the actual query index x. We omit the details of the multiple, adaptive-query version of Piano here and refer the interested readers to the original paper [ZPSZ24].

In the algorithm description, we use the following syntax of to capture the Piano PIR functionality with the batch-mode interface:

- $\mathsf{hint} \leftarrow \mathsf{PIR.Prep}(1^\lambda, \mathsf{DB})$: given the security parameter 1^λ and the database DB, generate the preprocessed PIR hint hint.
- $\mathsf{msg} \leftarrow \mathsf{PIR.BatchQuery}(\mathsf{hint}, \mathsf{batch})$: given the PIR hint and a batch of query indices $\mathsf{batch} \subseteq [n]$, the client generates the PIR query message msg.
- $\mathsf{ans} \leftarrow \mathsf{PIR.BatchAnswer}(\mathsf{DB}, \mathsf{msg})$: upon receiving the batched PIR query message msg, the server generates the batched answer ans.
- $(\beta, \mathsf{hint}') \leftarrow \mathsf{PIR.BatchRecover}(\mathsf{hint}, \mathsf{ans}, \mathsf{batch})$: given the batched answer ans and the PIR hint hint, recover the answers β and update the hint to hint'. Here, β is a set that includes all the successful query indices and their corresponding answers. That is, β includes the tuples $(i, \mathsf{DB}[i])$ for all $i \in \mathsf{batch}$ that are successfully queried.

C.2 Full Algorithm Description

The full algorithm description is in Figure 8.

Preprocessing. We use the same graph building algorithm as in Figure 7 to build a graph G from the vectors DB. We then combine the neighbor list of each vertex with its vector to build a new database $\mathsf{DB}' = \{(v_i, N(i))\}_{i\in[n]}$. Then, we randomly sample $\sqrt{n}$ starting vertices $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$ from $[n]$. We then run the client-side preprocessing algorithm of Piano and let the client store the hint hint. Further, we let the client download those starting vertices and their vectors and neighbor lists from the server.

Query for K-approximate nearest neighbors of vector $q \in \mathbb{R}^d$. We generalize the search algorithm to the following exploration process. The client can maintain two sets of vertices locally: 1) $\mathsf{visited}$ including all vertices that the client has already visited and stored their vectors and

neighbor lists, and 2) developed including all vertices that the client has already visited and retrieved all their neighbors' information. The client can maintain visited as a priority queue where the closer vertices to q are at the front. Each time the client can pick multiple vertices from visited and fetch their neighbors' information in parallel. The client will move those picked vertices from visited to developed, and add their neighbors to visited. We collect all those neighbors' indices as batch and issue a batched PIR query to the server. After receiving the batched answer, the client will recover all the successful queries and push them to visited. The client also needs to update the local hint hint after each query. We can repeat this process until the max hop number is reached. Finally, the client can output the top K nearest vertices in visited and developed to the query vector q.

We summarize the main result in the following theorem.

Theorem C.1. *Assume there exists one-way functions. Consider a database with n vectors in $\mathbb{R}^d$. Assuming a non-private graph-based ANN algorithm that preprocesses the database into a C-degree graph, and searches for the approximate nearest neighbors with H hops in the graph. Then, by applying the Piano PIR scheme, we can build a private ANN scheme with the following efficiency, while achieving the same search quality as the non-private graph ANN:*

- *Preprocessing: $\tilde{O}(n(d+C))$ client and server time and $O(n(d+C))$ communication;*
- *Query: $\tilde{O}(H \cdot \sqrt{Cn} \cdot (d+C))$ client and server time and $O(H \cdot \sqrt{Cn} \cdot (d+C))$ communication.*
- *Storage: $\tilde{O}(\sqrt{n} \cdot (d+C))$ client storage and no additional server storage except the database.*

Proof. The proof follows directly from the efficiency of the Piano PIR scheme when we consider a database with n entries and each entry stores a vector in $\mathbb{R}^d$ and a neighbor list of size C. Moreover, by applying the batched optimization we described in Section 3.3, we further reduce the computation and communication cost of each PIR query by $\sqrt{C}$. The privacy proof follows directly from the privacy guarantee of the Piano PIR scheme. ■

D Evaluation Details

D.1 Implementation Details

We detail our implementation of the two parts below.

Graph-based ANN. The graph-based ANN algorithm can be divided into two parts, the graph building part and the query part. The graph building part follows our description in Figure 7 and set the outbound number $C = 32$. The query part strictly follows our description in Figure 8.

Batched PIR. We implement a batch-mode version of the Piano PIR scheme [ZPSZ24] by first implementing the single-query version of the Piano PIR scheme with 128-bit security parameter, then wrapping it with a batch-mode interface. The interfact simply splits the whole database into B partitions, and then runs a single-query Piano PIR scheme on each partition parallelly. Given a batch of Q queries, we simply identitfy which partition each query belongs to, and then make Q/B queries at each partition to ensure privacy. We choose $B = 16$ and $Q = 32$ in our evaluation. Moreover, we implement the automatic maintainence for the client state. We keep track of the consumed hints in the client's space and automatically run another preprocessing when the hints are exhausted.

Pacmann: Privte Graph ANN with Preprocessing

Preprocessing.

- Server Side Preprocessing: *Input: a set of n vectors $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d \times n}$.*
  - Runs $G \leftarrow \mathsf{BuildGraph}(\mathsf{DB})$.
  - Randomly sample $\sqrt{n}$ starting vertices $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$ from $[n]$.
  - Let $\mathsf{DB}' = \{(v_i, N(i))\}_{i \in [n]}$ where $N(i)$ is the neighbor list of i in G.
    - Client Side Preprocessing:
      - Stores $\mathsf{hint} \leftarrow \mathsf{PIR.Prep}(1^\lambda, \mathsf{DB}')$. *// Involving communication with the server.*
      - Downloads the representative indices $u^1_{\text{start}}, \ldots, u^{\sqrt{n}}_{\text{start}}$ from the server.
      - For all $u \in \{u^i_{\text{start}}\}_{i \in [\sqrt{n}]}$, downloads $\mathsf{DB}'[u] = (v_u, N(u))$ from the server.

Query for K-approximate nearest neghbors of vector $q \in \mathbb{R}^d$.

- Parameters: max hop number H and beam search width m.

- Client Side Algorithm.
  - Let $\mathsf{visited} = \{u^i_{\text{start}}\}_{i \in [\sqrt{n}]}$ be a priority queue where the closest vertices to q are at the front.
  - Let $\mathsf{developed} = \emptyset$.
  - For $t = 1, 2, \ldots, H$:
    - Let $u_1, \ldots, u_m$ be the top m indices in $\mathsf{visited}$ and move them from $\mathsf{visited}$ to $\mathsf{developed}$.
    - Let $\mathsf{batch} = \cup_{i \in [m]} N(u_i)$ be the union of the neighbor lists of $u_1, \ldots, u_m$.
    - Remove those indices in batch that are already in $\mathsf{visited} \cup \mathsf{developed}$.
    - Send $\mathsf{msg} \leftarrow \mathsf{PIR.BatchQuery}(\mathsf{hint}, \mathsf{batch})$ to the server.
    - Upon receiving ans from the server, run $(\beta, \mathsf{hint}') \leftarrow \mathsf{PIR.Recover}(\mathsf{ans}, \mathsf{hint})$. where β is a set that includes all the successful query indices and their corresponding answers.
    - For each successful query tuple $(u, (v_u, N(u))) \in \beta$, add u to $\mathsf{visited}$ and store the vector v_u and neighbor list $N(u)$ locally.
    - Update the local PIR hint $\mathsf{hint} \leftarrow \mathsf{hint}'$.
  - Finally, for all $u \in \mathsf{visited} \cup \mathsf{developed}$, compute the distance $\Delta(v_u, q)$. Output the k indices with the smallest distances.

- Server Side Algorithm.
  - Upon receiving a PIR batch query message msg from the client, run $\mathsf{ans} \leftarrow \mathsf{PIR.BatchAnswer}(\mathsf{DB}', \mathsf{msg})$ and return ans.

Figure 8: Our private ANN scheme with preprocessing.

	MS-MARCO (3M)	SIFT (100M)
Preprocessing		
Graph Buliding Time	8.5 min	343.5 min
PIR Preprocessing	9.1 s	271.6 s
Communication	2.7 GB	59.6 GB
Online per query		
Latency	1.1 s	3.0 s
Computation Time	0.10 s	1.48 s
Online Communication	1.5 MB	14.4 MB
Rounds	20	32
Maintainence per query		
Time	0.19 s	1.99 s
Communication	60.1 MB	399.4 MB
Client Storage	0.6 GB	2.9 GB

Table 1: Detailed breakdown of our results on different datasets in the WAN setting. We list the preprocessing, online query and maintenance costs. The graph-build cost happens only once. The PIR preprocessing cost happens when each client joins the system. The online query cost is the cost on the critical path of the search queries. Followed by each online query, there is a necessary one-round maintenance to update the client state. We use 16 threads for the graph buiding and one thread for other parts. The corresponding qualities for the experiments are 0.266 MRR@100 for MS-MARCO and 0.90 recall@10 for SIFT.

D.2 Detailed Breakdown

Finally, we provide a detailed breakdown of the costs of our scheme in Table 1. We pick two representative parameter settings for the MS-MARCO dataset and the SIFT dataset, all achieving 90% quality of the state-of-the-art non-private ANN search algorithm. The graph building time is signifcant for both datasets, taking 8.5 minutes for the MS-MARCO dataset and 343.5 minutes for the SIFT dataset. However, the graph building only happens once at the server side. The PIR preprocessing is per-client, but it is relatively cheap, taking 9.1 seconds for the MS-MARCO dataset and 271.6 seconds for the SIFT dataset. The most expensive part is that during the preprocessing, the client has to streamingly scan over the whole index structure, taking large communication cost. For each online query, the latency and computation time match our analysis in Section 4.2. Notably, the communication cost on the critical path is relatively low, taking 1.5MB for the MS-MARCO dataset and 14.4MB for the SIFT dataset. Notice that the clien has to update its local state after each query. We see that the maintenance time per query is relatively cheap, but the communication cost is high, taking 60.1MB for the MS-MARCO dataset and 399.4MB for the SIFT dataset. Theoretically, the client stores around $\widetilde{O}(n)$ amount of local state. Empirically, we see that the client stores 0.6GB of data for the MS-MARCO dataset and 2.9GB of data for the SIFT dataset, and the scaling factor matches our theoretical analysis.

Discussion on quantization and comparing against Tiptoe. We noticed that the original Tiptoe implementation uses 4-bit quantization for the vectors to further trades off the search quality for the latency. In our evaluation, we use the full 32-bit precision for all the algorithms. Thus, the quality of the clustering-based algorithm should be considered an upper bound for the actual Tiptoe

algorithm. For the latency, the "Linear Algorithm" baseline should be a good approximation of the actual Tiptoe algorithm. As an example, if we extrapolate the number of Tiptoe's algorithm based on the Table 6 and Table 7 in the Tiptoe paper [HDCG+23] to the MS-MARCO dataset, the latency will be around 0.27 seconds [10].

Alternative Implementations. As alternatives, one can indeed use other PIR schemes to implement our graph-based ANN algorithm. For example, using another recent single-server PIR scheme, SimplePIR [HHCG+22] (used also in Tiptoe [HDCG+23]), comes with a tradeoff. For example, in the 10M SIFT dataset experiment, We can save the offline communication cost from roughly 6GB to around 300MB, but increase the online latency from 1.5s to roughly 90s based on our estimation as follows. We tested the throughput of the SimplePIR scheme on our server, which is around 10 GB/s. Then, we are making in total 25 rounds of graph explorations where each round has 96 parallel queries. The batching technique allows each individual query to be within a sub-database of 16 times smaller than the whole database (around 6GB). Therefore, the total estimated time would be $25 \times 96 \times \frac{6\text{GB}}{16 \times 10\text{GB/s}} \approx 90\text{s}$.

E Discussion on Theoretical Perspectives

We focused on the practical aspects of our scheme in the main body. Although graph-based ANN search has been empirically shown to be successful in practice, but the theoretical understanding of the graph-based ANN search is still very limited. Here, we try to provide some theoretical insights into the graph-based private ANN search given the existing theoretical results.

Definition E.1 ((c, r)-Approximate Nearest Neighbor)**.** Given n vectors $\mathsf{DB} = \{v_1, v_2, \ldots, v_n\} \in \mathbb{R}^{d \times n}$ and a distance function $\Delta(\cdot, \cdot)$, we say that an algorithm is a (c, r)-approximate nearest neighbor search algorithm if for any vector $q \in \mathbb{R}^d$ such that the true minimal distance between q and any vector in DB is at most r, the algorithm outputs an index i such that $\Delta(v_i, q) \leq c \cdot r$ with at least constant probability.

For the low-dimension case where $d = \Theta(\log n)$, we refer the reader to Prokhorenkova and Shekhovtsov [PS20] for the detailed discussion. Here, we will focus on the high-dimensional regime (also known as the sparse data case) such that the dimension $d = \omega(\log n)$, which is the most common setting for ANN search (recall that most embedding space is at least 100-dimensional).

There are two notable theoretical results that we can leverage to analyze the graph-based ANN search. Laarhoven [Laa18] proves the following theorem:

Theorem E.2 (Laarhoven [Laa18])**.** *Consider the database contains n independently random vectors in the unit sphere in $\mathbb{S}^{d-1}$ and the distance is measured by Euclidean distance. For $c > 1$, there exists a (c, r)-graph-based ANN search algorithm with the $O(n^{1+\rho+o(1)})$ space complexity and $O(n^{\rho+o(1)})$ query time complexity while taking only $O(1)$ hops in the graph, where*

$$\rho \geq \frac{c^4}{2c^4 - 2c^2 + 1}.$$

[10] The authors of Tiptoe reported the total core-second is 145 seconds for their experiment on a dataset with 360 millions 192-dimension vectors. The full Tiptoe system contains three parts: "preprocessing", "ranking" and "URL" where the "ranking" part corrsponds to our ANN search experiment. According to Table 7 in the paper, it should take about $(1.9/(6.5 + 1.9 + 0.6)) = 21\%$ of the cost. Thus, an estimation of the time on a single-core for the 3.2M size MS-MARCO dataset will be $145 \times 21\% \times \frac{3.2 \times 10^6}{360 \times 10^6} \approx 0.27$s, which is close to our simualted "Linear Algorithm" latency (0.25 seconds).

We call this setting the *average case setting*. Intuitively, we can think about n^ρ in the above theorem roughly denotes the average degree of the graph. For example, if we aim to have a 2-approximation ANN, $\rho \approx 0.64$. And we see that with the approximation factor c getting worse, $\lim_{c\to\infty} \rho(c) = \frac{1}{2}$.

On the other hand, Diwan et al. [DGM+24] studied the problem of building a navigatable graph. On a high-level, a navigatable graph provides the guarantee for "in-distribution" query for ANN search, that is, the query vector will be exactly some vector in the database. They showed the following theorem:

Theorem E.3 ([DGM+24])**.** *For any n vectors in $\mathbb{R}^d$, it is possible to build a navigatable graph with average degree of at most $2\sqrt{n \ln n}$. Moreover, the "greedy-routing" strategy always succeeds in finding the correct vector in the database with at most 2 hops.*

The above two theorems provide the theoretical insights that for the high-dimensional regime, to achieve a strong guarantee on the ANN search, the average degree of the graph will be roughly $n^{\frac{1}{2}+o(1)}$, and the query hop number will only be a constant. Therefore, if we use the same PIR technique to make the graph-based ANN search private, the underlying graph-information database is of size $n^{\frac{3}{2}+o(1)}$, where the total number of entries is n and each entry is of size $n^{1/2+o(1)}$. It is interesting to see that this is not a typical setting of the PIR literature, because the entry size is much larger than a constant. If we plug in the best parameters of the client-preprocessing PIR [ZPSZ24, NGH24] into the Laarhoven's algorithm, we will get the following result:

Theorem E.4. *Assume the existence of one-way function. For $c > 1$, there exists a (c, r)-graph-based private ANN search algorithm for Euclidean distance in the average case setting (random vectors on the unit sphere $\mathbb{S}^{d-1}$) with the following properties:*

- *Preprocessing cost: $\tilde{O}(n^{1+\rho+o(1)})$ communication and computation cost;*
- *Query cost:*
  - *$\tilde{O}(n^{1/2+\rho+o(1)})$ computation cost;*
  - *$\tilde{O}(n^{\rho+o(1)})$ communication cost;*
- *Storage cost:*
  - *Client: $\tilde{O}(n^{1/2})$;*
  - *Server: $\tilde{O}(n^{1+\rho+o(1)})$.*

Here,

$$\rho \geq \frac{c^4}{2c^4 - 2c^2 + 1}.$$

Specifically, we need to use the new result in Nguyen et al. [NGH24] for optimizing the client storage. Notice that based on the existing client-specific preprocessing PIR lower bounds [CK20, PY22, LMWY20], to privately access a data structure of size N, the product between the client storage S and the online time T satisfies that $S \times T = \Omega(N)$. In this sense, the above theoretical result is nearly tight in terms of the client storage and online query time if we follow the graph-based ANN paradigm: the client storage is $\tilde{O}(n^{1/2})$ and the online query time is $\tilde{O}(n^{1/2+\rho+o(1)})$, while the product matches the data structure size of $n^{1+\rho+o(1)}$.

Gap between Theory and Practice. Notably, the above theoretical results on graph-based ANN algorithms are based on the analysis on the "high-degree" graphs, where the average degree is $\Omega(\sqrt{n})$, and the query hop number is a small constant. In practice, we see a different combination: popular graph-based ANN algorithm implementations usually pick a much smaller average degree, e.g., 32 or 64, while making the query hop number to be larger (e.g. scaling with the logarithm of the database size). It remains an interesting open question whether there exists a strong theoretical result for small-degree graphs with a search process invoking large number of hops.