

# Efficient Interval Check in the Presence of Malicious Adversaries

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**Abstract.** We consider the following problem: Assuming that Alice and Bob have an integer interval  $[a, e]$  and an integer  $b$  respectively, for a commitment  $c$  to  $b$ , Alice and Bob jointly check whether  $b$  is within  $[a, e]$  without revealing their inputs, where either party may behave maliciously. A special case of the problem is the secure integer comparison in the malicious model. This problem mainly arises from location-based access control systems where one party needs to assure to the other party that its location is within some definite area.

Our main result is a constant-round protocol that exhibit the square of  $\log e$  communication and the square of  $\log e$  exponentiations with simulation-based security. At the heart of the construction is perfect  $k$ -ary index and corresponding zero-knowledge proof techniques. We consider a more general case of the problem where the interval is substituted by a union of intervals.

**Keywords:** private interval check, secure integer comparison, malicious model, zero-knowledge proof,  $k$ -ary tree index, location-based access control

## 1 Introduction

In this paper, we consider private interval check problem (PIC) where two party, having an integer interval  $[a, e]$  and an integer  $b$  respectively, want to check whether  $b \in [a, e]$  where either party may behave maliciously. A special case of PIC is the secure integer comparison problem in the malicious model. We consider a more general case of PIC where the interval is substituted by a union of intervals.

The main motivation for PIC is privacy protection in location-based access control systems [1–5]. In location-based access control systems, one party (Client) is willing to prove to the other party (Server) that her location, e.g., GPS coordinates  $(x, y)$ , is within Server's valid area, e.g., a rectangular area  $[(x_1, y_1), (x_2, y_2)]$  (where  $(x_1, y_1)$  and  $(x_2, y_2)$  denote the low-left and the upper-right points of the rectangular area), such that: (i) Client does not learn the valid area  $[(x_1, y_1), (x_2, y_2)]$ ; (ii) Server learns no information about Client location data  $(x, y)$ , beyond the result of whether  $(x, y) \in [(x_1, y_1), (x_2, y_2)]$ ; and

(iii) Client should not tamper with her location data or intermediate results to affect the final result.

The above problem can be formalized as a secure two-party computation problem: Two parties, Client and Server, each with an integer  $b$  and an integer interval  $[a, e]$  respectively, want to evaluate whether  $b \in [a, e]$ , such that: (i) Client can not learn the values  $a, e$ ; (ii) Server learns no information about value  $b$ ; and (iii) Client should not change  $b$  or intermediate results to affect the final result. As formerly stated, we call the problem “private interval check (PIC)”.

In the paper, we construct an efficient secure two-party protocol to treat PIC. Obviously, PIC is a special case of Private Set Intersection Cardinality problem (PSI-CA) [6–8], where two parties want to compute the intersection cardinality of their input sets without revealing their input set to the other one. There is then a direct question of why not to use existing PSI-CA protocols to solve PIC problem since, after all, there are many excellent protocols for PSI-CA [6–11]. One major reason is the inefficiency of these protocols to treat PIC, where an integer interval is treated simply as a set of all integers in the integer interval. However, integer interval is a consecutive integer set, which is redundant, and it would be inefficient to simply treat it without further treatment, such as compression. The other reason is that most of these protocols are based on the semi-honest model, where both parties are assumed to act according to their prescribed action in the protocol, which is unrealistic in our application scenario. A protocol is then needed to treat PIC efficiently in the malicious model.

Our major contribution is a private interval check protocol in the malicious model, where interval is not confined to an integer interval but a union of integer intervals. The major challenge is to first “compress” intervals and then prove the knowledge about it. To the best of our knowledge, ours is the first to solve the private interval check problem in the malicious model with constant round and  $O(\log^2 n)$  communication and exponentiations for the integer interval length  $n$ . The core of our protocol is the using of  $k$ -ary tree index and the accompanying zero-knowledge proof techniques. A simulation-based proof is given to the private interval check protocol. We also analyse our protocol’s complexity and give it an asymptotic optimization. Furthermore, a special case of our protocol is a secure integer comparison protocol [12–16] in the malicious model.

Besides location-based access control, there are other applications for our protocol, such as electronic election, credential systems, electronic auction, etc.

### 1.1 Related Works

Our work is related to Private Set Intersection (PSI) [6, 11, 9, 10] and Private Set Intersection Cardinality (PSI-CA) [7, 8, 6]. PSI have been widely looked at by researchers in the last few years due to their potential applications. PSI-CA is a special case of PSI where the output is the cardinality of intersection set but not the intersection. PIC can be seen as a special case of PSI-CA where the input sets are a set containing one integer and a set containing a series of consecutive integers, and the output is either 0 or 1. However, our work is different from the above works. The main difference of our work from PSI and

PSI-CA is that our work focuses on the special case of set, i.e., integer interval or union of integer intervals, which can be compressed to improve the efficiency of protocols. Moreover, the former PSI-CA protocols [7, 8] are not adapted to our application scenarios since their protocols are in the semi-honest model which is unrealistic to our application scenarios.

Our work is also related to the secure integer comparison – the well-known “Millionaires’ Problem” [12–16]. Due to its significant applications, such as electronic auction [15], secure interval check [14], location-based access control [17, 18], and proximity test [19–25], it has been studied extensively.

However, our protocol is different from these secure integer comparison protocols; almost all secure integer comparison protocols are based on the semi-honest assumption where each party follows the protocol with the exception that it keeps all its intermediate computations, which is not practical in our application scenarios. Our protocol don’t rely on the semi-honest model but assumes the existence of malicious parties which makes our schemes more practical than the formers.

There are other related works in the privacy protection of location-based access control [4, 5, 17, 2] and in location-based social networks [19]. However, these works either assume the honest Server or are based on the semi-honest assumption [4, 5, 17, 19] that are different from ours.

## 2 Preliminaries

### 2.1 Basic Notations

For a real number  $a$ ,  $\lfloor a \rfloor$  denotes the largest integer  $\leq a$ . The notation  $m \in_R S$  denotes that  $m$  is randomly chosen from a set  $S$ . The notation  $[x, y]$ , for two integers  $x$  and  $y$ , denotes an interval of integers, i.e.,  $[x, y] = \{z \in \mathbb{Z} : x \leq z \leq y\}$ . We say that  $m$  intervals  $[a_1, e_1], \dots, [a_m, e_m]$  are pairwise non-adjacent if  $e_i + 1 < a_{i+1}$  for  $1 \leq i \leq m - 1$ .

### 2.2 Hardness Assumptions

Our construction relies on the following two hardness assumptions.

**Definition 1 (Decisional Deffie-Hellman (DDH) assumption).** *Let  $\mathbb{G}$  be a group with order  $q$  and let  $g \in_R \mathbb{G}$ ,  $x, y, z \in_R \mathbb{Z}_q$ . The Decisional Deffie-Hellman assumption for  $\mathbb{G}$  is that it is infeasible to distinguish  $(g, g^x, g^y, g^z)$  from  $(g, g^x, g^y, g^{xy})$ .*

**Definition 2 (Discrete Logarithm (DL) assumption).** *Let  $\mathbb{G}$  be a group with order  $q$  and let  $g, h \in_R \mathbb{G}$ . The Discrete Logarithm assumption is that it is infeasible to find  $x \in_R \mathbb{Z}_q$  such that  $h = g^x$ .*

### 2.3 Commitment Scheme

In this paper, we use Pedersen commitment scheme [26]. Let  $q' = 2q + 1$  where  $q, q'$  are primes. Set  $\mathbb{G}$  to be the unique subgroup of  $\mathbb{Z}_{q'}^*$  of order  $q$ . Let  $\tilde{g}, \tilde{h}$  be two random generators of  $\mathbb{G}$ ; then a commitment to  $m \in \mathbb{Z}_q$  is defined as  $\text{com}(m, r) = \tilde{g}^m \tilde{h}^r$  where  $r \in_R \mathbb{Z}_q$ . Commitment to a set is defined as follow.

**Definition 3 (Commitment to a set).** Let  $B = \{n_0, \dots, n_t\}$  be a subset of  $\mathbb{Z}_q$ . Set, for  $0 \leq i \leq t$ ,  $c_i = \text{com}(n_i, r_{n_i})$  where  $r_{n_i} \in \mathbb{Z}_q$ . Then the set  $C = \{c_0, \dots, c_t\}$  is said to be a commitment to  $B$ .

The commitment scheme is computationally binding and perfectly hiding.

### 2.4 Homomorphic Encryption Scheme

We use a standard variant of ElGamal encryption scheme [27]. We use the same group  $\mathbb{G}$  used for the Pedersen commitment scheme. Let  $g, h$  be two random generators in  $\mathbb{G}$ ; then the public key is  $(g, h)$  and the secret key is  $k = \log_g h$ . To encrypt a message  $m \in \mathbb{Z}_q$ , choose  $y \in_R \mathbb{Z}_q$ , and compute  $E(m) = (g^y, h^y \times g^m)$ . To decrypt  $(\alpha, \beta)$ , first compute  $\beta/\alpha^x$ , then search a lookup table of  $(g^m, m)$  to find  $m$ . It is easy to find that the decryption scheme is very inefficient. Fortunately, we don't need any decryption but only need verification of whether  $g^m = 1$ . Note that  $g^m = 1$  if and only if  $m = 0$ .

It is easy to verify that the modified ElGamal scheme is *additively homomorphic*, i.e.,  $E(m_1 + m_2) = E(m_1)E(m_2)$ . It follows by repeated addition that  $E(em) = E(m)^e$  for an integer  $e$ .

### 2.5 Secure Two-Party Computation

A two-party protocol problem is cast by specifying a random process that maps pairs of inputs to pairs of outputs. Let  $f$  be a two-party functionality, i.e.  $f = (f_1, f_2) : \{0, 1\}^* \times \{0, 1\}^* \mapsto \{0, 1\}^* \times \{0, 1\}^*$ , and let  $\pi$  be a two-party protocol for computing  $f$ . The security of  $\pi$  in the malicious model [28, §7.2] is defined as follow.

**Definition 4.** Let  $f$  and  $\pi$  be as above. Protocol  $\pi$  is said to securely compute  $f$  with abort in the presence of malicious adversaries if for every probabilistic polynomial-time adversary  $\mathcal{A}$  for the real model, there exists a probabilistic polynomial-time (p.p.t.) adversary  $\mathcal{S}$  for the ideal model, such that for every  $I \subset \{1, 2\}$ ,

$$\{\text{IDEAL}_{f, \mathcal{S}(z), I}(x, y, n)\}_{x, y, z \in \{0, 1\}^*, n \in \mathbb{N}} \stackrel{c}{=} \{\text{REAL}_{\pi, \mathcal{A}(z), I}(x, y, n)\}_{x, y, z \in \{0, 1\}^*, n \in \mathbb{N}},$$

where  $I \subset \{1, 2\}$  denotes the set of corrupted parties,  $(x, y)$  denote the inputs of  $\pi$ ,  $z$  is the auxiliary input to  $\mathcal{A}$ , and  $n$  is the security parameter.

## 2.6 Zero-Knowledge Proofs

For a Proof of Knowledge (PK) we use the definition from [29].

**Definition 5.** A two-party protocol  $(P, V)$  is a proof of knowledge (PK) for a relation  $R = \{(x, w)\} \subset \{0, 1\}^* \times \{0, 1\}^*$  with knowledge error  $0 \leq \kappa \leq 1$  if the following properties are satisfied:

- Completeness: If  $P$  and  $V$  follow the protocol on input  $x$  and private input  $w$  to  $P$  where  $(x, w) \in R$ , then  $V$  always accepts.
- Knowledge soundness (or validity): If a cheating prover  $P^*$  has probability  $\epsilon$  of convincing  $V$  to accept  $x$ , there exists an expected polynomial-time algorithm  $E$ , called the knowledge extractor, such that when given rewindable black-box access to  $P^*$ ,  $E$  outputs a witness  $w$  for  $x$  with probability  $\epsilon - \kappa$ .

The proof system  $(P, V)$  is zero-knowledge if there exists a p.p.t. algorithm  $\mathcal{S}$ , called the simulator, such that for any  $(x, w) \in R$  and any p.p.t. algorithm  $V^*$ , the outputs of  $V^*(x)$  after interacting with  $P(w)$  and that of  $\mathcal{S}(w)$  are computationally indistinguishable.

When presenting protocols we express Zero Knowledge (ZK) proofs using the notation introduced by Camenisch and Stadler [30]:

$$PK\{(\alpha, \beta, \dots) : \text{statements involving } \alpha, \beta, \dots\}$$

means the prover is proving knowledge of  $(\alpha, \beta, \dots)$  such that these values satisfy statements.

## 2.7 Perfect Binary Index

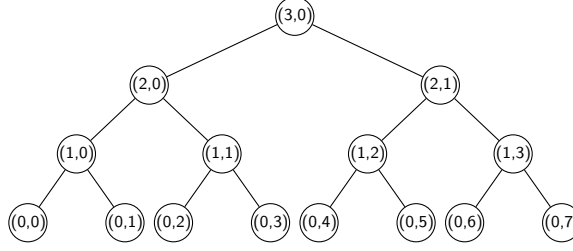
The paper [14] presents perfect binary index. We summarize their definitions as follows.

**Definition 6 (Tree node).** A tree node is a data structure that consists of a unique label  $(h, o)$  and possibly two pointers left and right to other tree nodes. The label has two components: the height  $h$  and the order  $o$ . A leaf node is a tree node with a label  $(0, o)$  and no pointers.

**Definition 7 ( $\ell$  Perfect Binary Tree ( $\ell$  PBT)).** An  $\ell$  perfect binary tree is a binary tree with a set of leaf nodes  $L = \{(0, 0), (0, 1), \dots, (0, 2^\ell - 1)\}$  and a set of non-leaf nodes  $NL$  such that  $(\ell, 0) \in NL$  and for all  $(h, o) \in NL$ , there exists  $(h-1, 2o), (h-1, 2o+1) \in (L \cup NL)$  with  $(h, o).left = (h-1, 2o)$ ,  $(h, o).right = (h-1, 2o+1)$ . In an  $\ell$  PBT, the root node is the node  $(\ell, 0)$ .

Figure 1 shows a 3 PBT.

**Definition 8 (Coverage).** Given an  $\ell$  PBT, we say a tree node  $(h_1, o_1)$  covers a leaf node  $(0, o_2)$  if there exist a path from  $(h_1, o_1)$  to  $(0, o_2)$  in the tree (e.g., if  $o_1 \times 2^{h_1} \leq o_2 < (o_1 + 1) \times 2^{h_1}$ ). The covering set of a given leaf node  $v$  is the set of

**Fig. 1.** 3 Perfect Binary Tree

all nodes in the PBT that cover  $v$  (e.g., all nodes on the path from  $v$  to the root). The coverage of a tree node  $v = (h_1, o_1)$  is the set of all leaf nodes covered by  $v$ . The pointer  $v.\text{leftLeaf}$  [ $v.\text{rightLeaf}$ ] returns the left [right] most leaf node in the coverage of  $v$  ( $v.\text{leftLeaf} = (0, o_1 \times 2^{h_1})$ ,  $v.\text{rightLeaf} = (0, (o_1 + 1) \times 2^{h_1} - 1)$ ).

**Definition 9 (Representer set and minimal representer set).** Given an  $\ell$  PBT, a representer (set) of a set of leaf nodes  $L' \subseteq L$  is a set of nodes  $R \subseteq (L \cup NL)$  such that

- for all nodes  $v \in L'$ , there exists a node in  $R$  that covers  $v$ , and
- for all nodes  $v \in R$ , there is no leaf node  $v' \notin L'$  that is covered by  $v$ .

A representer  $R$  for the set of leaf nodes  $L'$  is minimal, if there is no other representer  $R'$  of  $L'$  with  $|R'| < |R|$ .

## 2.8 Perfect $k$ -ary Index

In this paper, we use a generalized notion of the perfect binary index in Section 2.7, i.e., perfect  $k$ -ary index. The generalization is direct. We only give the details of the notion of  $\ell$  perfect  $k$ -ary tree ( $\ell$  PKT). Other related notions can be treated similarly.

**Definition 10 ( $\ell$  Perfect  $k$ -ary tree ( $\ell$  PKT)).** An  $\ell$  perfect  $k$ -ary tree ( $k \geq 2$ ) is a  $k$ -ary tree with a set of leaf nodes  $L = \{(0, 0), (0, 1), \dots, (0, k^\ell - 1)\}$  and a set of non-leaf nodes  $NL$  such that  $(\ell, 0) \in NL$  and for all  $(h, o) \in NL$ , there exists  $(h-1, ko), (h-1, ko+1), \dots, (h-1, ko+k-1) \in (L \cup NL)$  with  $(h, o).c_1 = (h-1, ko), \dots, (h, o).c_k = (h-1, ko+k-1)$ . In an  $\ell$  PKT, the root node is the node  $(\ell, 0)$ .

Figure 2 shows a 2 Perfect 3-ary Tree (P3T).

**Lemma 1 ([14](Lemma 6)).** Let  $R$  be a minimal representer of a set of leaf nodes. For each node  $n \in R$ , no other node  $n' \in R$  is a descendant of  $n$ .

**Lemma 2 ([14](Lemma 3)).** Let  $R$  be a minimal representer for  $\{(0, 0), \dots, (0, e)\}$  in an  $\ell$  PKT. For each level  $0 \leq i \leq \ell$ , there can be at most  $k-1$  nodes  $v \in R$  such that  $v.h = i$ .

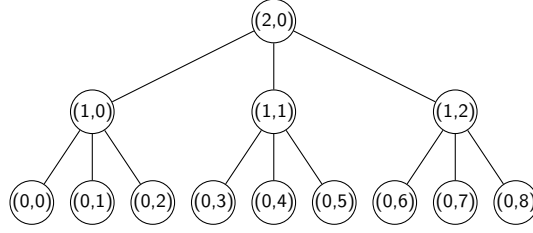


Fig. 2. 2 Perfect 3-ary Tree

**Lemma 3** ([14](Lemma 5)). *Given an  $\ell$  PKT, let  $R$  be a minimal representer for the set of leaf nodes  $\{(0, a), \dots, (0, e)\}$  and let  $B$  be the covering set for the leaf node  $(0, b)$ . Then  $a \leq b \leq e$  if and only if  $|R \cap B| = 1$ .*

The above three lemmas are the generalizations of the lemmas in [14]. The proof of these three lemmas is similar with those in [14] and we omit them.

**Corollary 1.** *Let  $L_i = [a_i, e_i]$ , for  $1 \leq i \leq m$ . Let  $R_i$ , for  $1 \leq i \leq m$ , be the minimal representer set of  $L_i$  and let  $R$  be the minimal representer set of  $\cup_{i=1}^m L_i$  in an  $\ell$  PKT. If  $L_i$  are pairwise non-adjacent, i.e.,  $e_i + 1 < a_{i+1}$  for  $1 \leq i \leq m - 1$ , then  $R = \cup_{i=1}^m R_i$ .*

*Proof.* Since  $L_i$ , for  $1 \leq i \leq m$ , are pairwise non-adjacent, we get  $R_i \cup R_j = \emptyset$  for different  $i, j$  from Definition 9. Then we have  $R = \cup_{i=1}^m R_i$ .

**Corollary 2.** *Let  $L_i, R$  be as in Corollary 1 and  $B$  be the covering set of  $b$  in the  $\ell$  PKT. Then  $b \in \cup_{i=1}^m L_i$  if and only if  $|R \cap B| = 1$ .*

The notion of PKT gives a bijection between a set of integers and a set of leaf nodes in the PBT, such as the integer interval  $[a, e]$  is injected to the set  $\{(0, a), (0, a + 1), \dots, (0, e)\}$ . In the following sections, we will use the notations  $[a, e]$  to denote either the integer interval  $[a, e]$  or the set of leaf nodes  $\{(0, a), (0, a + 1), \dots, (0, e)\}$  if without ambiguity.

We define a bijection  $g(h, o) = \sum_{j=0}^{h-1} k^{\ell-j} + o$  between the set of all nodes in an  $\ell$  PKT and the integer interval  $[0, (k^{\ell+1} - 1)/(k - 1)]$ . By using the bijection  $g$  each node  $(h, o)$  in an  $\ell$  PKT is identical to a unique integer  $g(h, o)$ . In the following part of the paper, while mentioning a node, it would relate either to  $(h, o)$  or to its integral form  $g(h, o)$ . We would interchangeably use them without ambiguity.

### 3 Commitment to the Covering Set of an Integer

In this section, we give a protocol to prove the knowledge of commitment to the covering set of an integer. Specifically, setting  $B$  be the covering set of an integer  $b \in [0, k^\ell]$  in an  $\ell$  PKT, Client can convince Server, who only knows a commitment to  $b$ , that a set is a commitment to  $B$ . We first give a result for  $B$ .

**Lemma 4.** *Let  $b, B, k, \ell$  be as above. Then  $B = \{(0, b), (1, \lfloor b/k \rfloor), (2, \lfloor b/k^2 \rfloor), \dots, (\ell, \lfloor b/k^\ell \rfloor)\}$ .*

*Proof.* By Definition 10, the coverage of a node  $(h, o)$  is  $\{(0, k^h \times o), \dots, (0, k^h \times (o+1) - 1)\}$ . Assuming that  $(i, j)$  is the node that covers  $(0, b)$  in the level  $i$ ,  $0 \leq i \leq \ell$ , then  $k^i \times j \leq b \leq k^i \times (j+1) - 1$ . We have  $b/k^i - 1 + 1/k \leq j \leq b/k^i$  and so  $j = \lfloor b/k^i \rfloor$ . The proof is complete.

Let  $B, b$  be as in Lemma 4, and let  $C, c$  be commitments to  $B, b$  respectively. We now show a two-party protocol by which Client can prove to Server, where Server only knows  $c$ , that  $C$  is a commitment to  $B$  without revealing  $b$  and  $B$ .

**Protocol 1**

- Common input: A string  $c$  and a set  $\{c_0, \dots, c_\ell\}$ , where  $c, c_0, \dots, c_\ell \in \mathbb{G}$ .
- Auxiliary input for Client: A tuple  $(b, r)$  such that  $c = \text{com}(b, r)$ , where  $b, r \in \mathbb{Z}_q$ .
- Initial message: Client computes
  1.  $c_{b_i} = \text{com}(b_i, r_{b_i})$ , for  $i = 0, \dots, \ell - 1$ , where  $r_{b_i} \in_R \mathbb{Z}_q$  and  $b_i$  is the  $i$ th digit (from right to left) in the  $k$ -ary notation of  $b$ .
  2.  $e_0 = b$  and  $c_{e_0} = c_b$ .
  3. for  $1 \leq i \leq \ell$ ,  $e_i = (e_{i-1} - b_{i-1})/k$  and  $c_{e_i} = \text{com}(e_i, r_{e_i})$ , where  $r_{e_i} \in_R \mathbb{Z}_q$ .
- The protocol:
  1. Client sends  $\{c_{b_0}, \dots, c_{b_{\ell-1}}\}$  and  $\{c_{e_0}, \dots, c_{e_\ell}\}$  to Server.
  2. For each  $0 \leq i \leq \ell - 1$ , Client proves to Server that  $c_{b_i}$  commits to the  $i$ th digit  $b_i$  in the  $k$ -ary notation of  $b$ , i.e.,

$$PK\{(b_i, r_i) : c_{b_i} = g^{b_i} h^{r_i} \wedge b_i \in [0, k-1]\}, \text{ for } 0 \leq i \leq \ell - 1$$

and

$$PK\{(\theta) : c / \prod_{i=0}^{\ell-1} c_{b_i}^{k^i} = h^\theta\}.$$

3. For  $1 \leq i \leq \ell$ , Client proves to Server that  $e_i = (e_{i-1} - b_{i-1})/k$ , i.e.,

$$PK\{(\delta_i) : c_{e_{i-1}} / (c_{b_{i-1}} c_{e_i}^k) = h^{\delta_i}\}, \text{ for } 1 \leq i \leq \ell.$$

4. Client proves to Server that  $\{c_0, \dots, c_\ell\}$  is a set of commitments of  $B$ , i.e., for  $0 \leq i \leq \ell$ ,

$$PK\{(\tau_0, \tau_1, \dots, \tau_\ell) : c_0 / (c_{e_i} g^{f_i}) = h^{\tau_0} \vee c_1 / (c_{e_i} g^{f_i}) = h^{\tau_1} \vee \dots \vee c_\ell / (c_{e_i} g^{f_i}) = h^{\tau_\ell}\},$$

$$\text{where } f_i = \sum_{j=0}^{i-1} k^{\ell-j}.$$

Note that  $\{c_0, \dots, c_\ell\}$  is a shuffle of a commitment to  $B$ , i.e., each  $c_i$  committing to which node in  $B$  is unknown to Server.



*Remark 1.* In Step 2, the first  $\ell$  PKs can be achieved using the range proof techniques in [31] and the last PK is just a proof of knowledge of discrete logarithm. The PK in Step 4 can be evaluated using the batch proof techniques in [32].

*Remark 2.* The complexity of Protocol 1: The initial message step needs  $4\ell$  exponentiations in  $\mathbb{G}$ ; In Step 2, the first  $\ell$  PKs needs  $O(\ell \log k)$  exponentiations in  $\mathbb{G}$  using the range proof protocol in [31] and the last PK needs  $\ell + 3$  exponentiations in  $\mathbb{G}$ ; Step 3 needs  $4\ell$  exponentiations in  $\mathbb{G}$ ; Step 4 needs  $O(\ell^2)$  exponentiations in  $\mathbb{G}$  [33, 32]. The total computation is  $O(\ell \times \max(\ell, \log k))$  exponentiations in  $\mathbb{G}$ . The total communication is  $O(\ell \times \max(\ell, \log k)|\mathbb{G}|)$  bits.

**Theorem 1.** *Protocol 1, when constructed with a secure ZK protocol, is a zero-knowledge proof for the assertion that  $\{c_0, \dots, c_\ell\}$  is a shuffle of a commitment to  $B$ .*

*Proof.* Step 2 proves that  $c_{b_i}$  commits to the  $i$ th digit in the  $k$ -ary notation of  $b$ . Step 3 proves that  $c_{e_i}$  commits to  $\lfloor b/k^i \rfloor$ . Step 4 illustrates that  $\{c_0, \dots, c_\ell\}$  and  $\{c_{e_0}g^{f_0}, \dots, c_{e_\ell}g^{f_\ell}\}$  commit to the same set, where  $c_{e_i}g^{f_i}$  commits to the node  $(i, \lfloor b/k^i \rfloor)$  in  $B$ . In all, completeness and soundness are complete.

Zero-knowledge property follows from the fact of perfectly hiding property of the commitment scheme and of zero-knowledge property of each ZK protocol in Protocol 1.

## 4 Private Interval Check Protocol

We now consider the private interval check problem. We first give the problem a formal definition and then present a high level description of our protocol. Finally, we present the detailed protocol.

### 4.1 Definitions and Overview

We consider a more general case of the private interval check problem where the interval may not be an interval but a union of intervals. Let  $L_i = [a_i, e_i]$ , for  $1 \leq i \leq m$ , be  $m$  pairwise non-adjacent intervals, and let  $R_i$  be the minimal representer set of  $L_i$  in an  $\ell$  PKT. Let  $R$  be the minimal representer set of  $L = \cup_{i=1}^m L_i$ . Let  $b$  be a nonnegative integer  $\leq k^\ell - 1$  and  $B$  be its covering set in the  $\ell$  PKT.

**Definition 11 (Private Interval Check of Committed Integer).** *Let  $L, b$  be as above. Set  $c = \text{com}(b, r)$  be a commitment of  $b$ . The function of private interval check of committed integer  $\mathcal{F}_{\text{PIC}}$  is defined as*

$$((b, c), (L, c)) \mapsto (\lambda, |\{b\} \cap L|).$$

**Definition 12.** *Let  $\Pi$  be a protocol to compute  $\mathcal{F}_{\text{PIC}}$ .  $\Pi$  is said to securely compute  $\mathcal{F}_{\text{PIC}}$  with abort in the presence of malicious adversaries if for every*

probabilistic polynomial-time adversary  $\mathcal{A}$  for the real model, there exists a probabilistic polynomial-time adversary  $\mathcal{S}$  for the ideal model, such that for every  $I \subset \{\text{Client}, \text{Server}\}$ ,

$$\{\text{IDEAL}_{\mathcal{F}_{\text{PTC}}, \mathcal{S}(z), I}((b, c), (L, c))\} \stackrel{c}{=} \{\text{REAL}_{\Pi, \mathcal{A}(z), I}((b, c), (L, c))\}.$$

Suppose that Client has  $(b, c)$  and that Server has  $(L_1, \dots, L_m, c)$ . By Corollary 2,  $b \in L$  if and only if  $|R \cap B| = 1$ . Therefore, we only need to check whether  $|R \cap B| = 1$  in order to check whether  $b \in L$ . Our protocol functions as follows.

- Client computes a commitment  $C$  to  $B$ , and proves the knowledge of  $C$  to Server using protocol 1.
- Server evaluates the minimal representer  $R$  of  $L_1, \dots, L_m$  in the  $\ell$  PKT and computes  $f(x) = \prod_{a_i \in R} (x - a_i) = \sum_{i=0}^v \alpha_i x^i$  where  $v = |R|$ .
- Server encrypts  $\alpha_i$ , for  $i = 0, \dots, v$ , using its ElGamal encryption function  $E(\cdot)$  and prove to Client that  $E(\alpha_i)$  is a correct encryption.
- For each  $n_i \in B$ , Client evaluates  $w_i = E(s_i f(n_i))$  where  $s_i \in \mathbb{Z}_q / \{0\}$  and proves to Server that it is evaluated correctly. Note that  $n_i \in B \cap R$  if and only if  $f(n_i) = 0$ .
- Server decrypts  $w_i$  to get  $g^{s_i f(n_i)}$  and counts the number of  $w_i$  if the corresponding decryption is  $g^{s_i f(n_i)} = 1$  and denotes the count as  $e$ . Note that  $n_i \in B \cap R$  if and only if  $g^{s_i f(n_i)} = 1$  and that  $g^{s_i f(n_i)}$  would be a random element to Server if  $n_i \notin B \cap R$ .
- Server accepts that  $b \in L$  if and only if  $e = 1$ . Note that  $e$  is the number of node in  $B \cap R$ .

## 4.2 A Concrete Construction

We now present the detailed protocol.

### Protocol 2 (Private Interval Check of Committed Integer)

- Common input: A string  $c \in \mathbb{G}$ .
- Auxiliary input for Client: A tuple  $(b, r)$  such that  $c = \text{com}(b, r)$  where  $b, r \in \mathbb{Z}_q$ .
- Auxiliary input for Server:  $m$  pairwise non-adjacent intervals  $L_1, \dots, L_m$ .
- Initial message: For two positive integer  $k$  and  $\ell$ ,
  - Client computes  $b$ 's covering set  $B$  in the  $\ell$ -PKT.
  - Server computes  $L$ 's minimal representer set  $S$  in the  $\ell$ -PKT and computes  $f(x) = \prod_{a_i \in R} (x - a_i) = \sum_{i=0}^v \alpha_i x^i$  where  $v = |R|$ .
- The protocol:
  1. Client proves the knowledge of a commitment to  $B$  by invoking Protocol 1 with Client's input  $(c, b, r)$ , denoting the ZK constructed for Protocol 1 as  $P_1$ . Suppose that the output of Protocol 1 is the set  $C = \{c_i : c_i = \text{com}(n_i, \delta_i), n_i \in B, \delta_i \in \mathbb{Z}_q, 0 \leq i \leq \ell\}$ .
  2. Client sends  $C$  and  $P_1$  to Server.
  3. Server verifies  $P_1$ , and aborts if it fails.
  4. Server evaluates  $E_i = E(\alpha_i) = (g^{r_i}, g^{\alpha_i} h^{r_i})$ ,  $r_i \in \mathbb{Z}_q$  for  $i = 0, \dots, v$ .

5. *Server creates*

$$P_2 = PK\{(\alpha_0, \dots, \alpha_k, r_0, \dots, r_k) : E_{i,1} = g^{r_i} \wedge E_{i,2} = g^{\alpha_i} h^{r_i} \text{ for } i = 0, \dots, v\},$$

where  $E_{i,1}$  and  $E_{i,2}$  denote the first and the second item of  $E_i$  respectively.

6. *Server sends  $(E_0, \dots, E_v)$  and  $P_1$  to Client.*

7. *Client verifies  $P_2$ , and aborts if it fails.*

8. *Client homomorphically evaluates  $f$  at elements in  $B$  by computing*

$$v_i = (\prod_{j=0}^v E_{j,1}^{n_i^j}, \prod_{j=0}^v E_{j,2}^{n_i^j})$$

for each  $n_i \in B$  in random order, then computes  $w_i = (v_{i,1}^{s_i}, v_{i,2}^{s_i})$  for  $s_i \in_R \mathbb{Z}_q / \{0\}$ . Note that  $w_i = E(s_i f(n_i))$ .

9. *Client creates the proof*

$$P_3 = PK\{(n_0, \dots, n_\ell, s_0, \dots, s_\ell, \delta_0, \dots, \delta_\ell) : w_i = (\prod_{j=0}^v E_{j,1}^{n_i^j s_i}, \prod_{j=0}^v E_{j,2}^{n_i^j s_i}) \wedge$$

$$c_i = \text{com}(n_i, \delta_i), \text{ for } i = 0, \dots, \ell\}.$$

10. *Client sends  $(w_0, \dots, w_\ell, P_3)$  to Server.*

11. *Server verifies  $P_3$ , and aborts if verification fails. Server also checks that  $s_i \neq 0$  by verifying that  $w_i \neq (1, 1)$  for  $i = 0, \dots, \ell$ .*

12. *Server initializes a counter  $e = 0$ , evaluates  $D(w_i)$  to get  $g^{s_i f(n_i)}$  and increments  $e$  if  $g^{s_i f(n_i)} = 1$ .*

13. *Server outputs  $e$ .*

Some explanations are needed for  $P_2$  and  $P_3$ . The ZK of  $P_2$  needs a proving the knowledge of the discrete logarithm  $\alpha_i$  and a proving the equality of the discrete logarithm  $r_i$ . The ZK of  $P_3$  is more involved. For notational simplicity, for each  $n \in B$ , we set  $w = (w_1, w_2) = (\prod_{j=0}^v E_{j,1}^{n^j s}, \prod_{j=0}^v E_{j,2}^{n^j s})$  and set, for  $j = 1, \dots, v$ ,  $d_j = \text{com}(n^j, u_j)$  where  $s, u_j \in_R \mathbb{Z}_q$ . For each  $n \in B$ , Client creates

$$PK\{(n, u_1, \delta_2, \dots, \delta_v) : d_1 = \text{com}(n, u_1) \wedge d_2 / d_1^n = \text{com}(0, \delta_2) \wedge \dots \wedge d_v / d_{v-1}^n = \text{com}(0, \delta_v)\}$$

and

$$PK\{(\beta_1, \dots, \beta_v, \delta_1, \dots, \delta_v, s) : w_1 / E_{1,1} = \prod_{j=1}^v E_{j,1}^{\beta_j s} \wedge w_2 / E_{1,2} = \prod_{j=1}^v E_{j,2}^{\beta_j s} \wedge$$

$$d_1 = \text{com}(\beta_1, \delta_1) \wedge \dots \wedge d_v = \text{com}(\beta_v, \delta_v)\},$$

where the first ZK proves that  $d_j$  commits to  $n^j$  for  $j = 1, \dots, v$  and the second ZK proves that  $w$  is computed correctly by the product of  $E_i$ 's correct exponentiation.

*Remark 3.* The complexity of Protocol 2: Step 1 needs  $O(\ell \times \max(\ell, \log k))$  exponentiations in  $\mathbb{G}$ ; Step 4 needs  $3(v+1)$  exponentiations in  $\mathbb{G}$ ; Step 5 needs  $8(v+1)$  exponentiations in  $\mathbb{G}$ ; Step 8 needs  $2(v+2)\ell$  exponentiations in  $\mathbb{G}$ ; Step 9 needs  $O(v\ell)$  exponentiations in  $\mathbb{G}$ . The total computation is  $O(\ell \times \max(\ell, \log k, v))$  exponentiations in  $\mathbb{G}$ . The total communication is  $O(\ell \times \max(\ell, \log k, v)|\mathbb{G}|)$  bits.

**Theorem 2.** *Protocol 2, when constructed with a secure ZK protocol, is a secure protocol to compute  $\mathcal{F}_{\text{PIC}}$  assuming the DDH and DL assumptions hold.*

*Proof.* We separately prove security in the case that no parties are corrupted, the case that *Client* is corrupted, and the case that *Server* is corrupted.

*No parties are corrupted.* Step 1 ensures that  $C$  is a commitment to  $B$ . Step 4 and Step 5 ensure that the function  $f(t)$  is encrypted correctly. Step 9 ensures that, for each  $n_i \in B$ , the encryption  $E(s_i f(n_i))$  is computed correctly. Since  $\mathbb{G}$  is prime order and  $s_i \neq 0$  it must be that  $g^{s_i f(n_i)} = 1$  if and only if  $f(n_i) = 0$  in Step 12. Hence,  $e$  is the number of elements  $n_i$  in  $B$  such that  $f(n_i) = 0$ . On the other hand,  $f(t) = 0$  if and only if  $t \in R$  by the definition of  $f(t)$  which results in that  $e$  is the number of elements of  $B \cap R$ . By Corollary 2,  $b \in L$  if and only if  $|B \cap R| = 1$ . Therefore,  $b \in L$  if and only if  $e = 1$  and then the protocol is correct.

*Server is corrupted.* Let  $\mathcal{A}$  denote an adversary controlling *Server*. We construct a simulator  $\mathcal{S}$  as follows.

1.  $\mathcal{S}$  evaluates, for  $i = 0, \dots, \ell$ ,  $c_i = \text{com}(n_i, \delta_i)$  for randomly chosen  $(n_i, \delta_i)$ , and forges the proof  $P_1$ .
2.  $\mathcal{S}$  sends  $c_0, \dots, c_\ell$  and  $P_1$  to  $\mathcal{A}$ .
3.  $\mathcal{S}$  receives from  $\mathcal{A}$  the encrypted polynomial  $E_0, \dots, E_v$  and  $P_2$ . If  $P_2$  is invalid or if  $\mathcal{A}$  has aborted,  $\mathcal{S}$  stops and returns  $\perp$  to the trusted party. Otherwise,  $\mathcal{S}$  receives  $\alpha_0, \dots, \alpha_v$  from  $\mathcal{A}$  and verifies the validity.
4.  $\mathcal{S}$  evaluates  $w_0, \dots, w_\ell$  and creates the proof  $P_3$ .
5.  $\mathcal{S}$  sends  $w_0, \dots, w_\ell$  and  $P_3$  to  $\mathcal{A}$ .
6.  $\mathcal{S}$  outputs whatever  $\mathcal{A}$  does.

To prove that  $\mathcal{A}$ 's views in the real and simulated executions are computationally indistinguishable, we construct a sequence of games and show that the corresponding random variables  $G_i^{\mathcal{A}(z)}(c, b, L)$  that consist of the view of  $\mathcal{A}$  in game  $G_i$  are computationally indistinguishable. Recall that the commitment scheme *com* is perfectly hiding, and that the ElGamal encryption scheme is semantically secure.

*Game  $G_0$ :* The simulated execution.

*Game  $G_1$ :*  $\mathcal{A}$  follows Protocol 2 except that  $\mathcal{A}$  chooses a set  $S'$  to compute  $f(t)$  which is the minimal representer set of a set  $L'$  where  $L \neq L'$ . In this case, the output of  $\mathcal{A}$  is the same as the output of  $\mathcal{S}$  where the input is  $L'$ . Therefore,  $G_0^{\mathcal{A}(z)}(c, b, L)$  and  $G_1^{\mathcal{A}(z)}(c, b, L)$  are computationally indistinguishable.

*Client is corrupted.* Let  $\mathcal{A}$  denote an adversary controlling *Client*. We construct a simulator  $\mathcal{S}$  as follows.

1.  $\mathcal{S}$  receives  $C$  and  $P_1$  from  $\mathcal{A}$ , verifies  $P_1$ , and extracts  $(n_0, \delta_0), \dots, (n_\ell, \delta_\ell)$ .
2.  $\mathcal{S}$  evaluates, for  $i = 0, \dots, v$ ,  $E_i = E(\alpha_i) = (g^{r_i}, g^{\alpha_i} h^{r_i})$  for randomly chosen  $(r_i, \alpha_i)$ , and forges the proof  $P_2$ .
3.  $\mathcal{S}$  sends  $E_0, \dots, E_v$  and  $P_2$  to  $\mathcal{A}$ .
4.  $\mathcal{S}$  receives  $w_0, \dots, w_\ell$  and  $P_3$  from  $\mathcal{A}$ .

Since the commitment scheme is perfectly hiding and the ElGamal encryption scheme is semantically secure, we can see that the view of  $\mathcal{A}$  is computationally indistinguishable from the view of  $\mathcal{S}$ .

In all, the proof is complete.

**Corollary 3.** *If  $L = [0, b]$ , Protocol 2, when constructed with a secure ZK protocol, is a secure integer comparison protocol in the malicious model assuming the DDH and DL assumptions hold.*

### 4.3 Asymptotic Complexity Analysis

We now give an asymptotic analysis of the computational and communication costs of our protocol.

Let  $b, k, \ell, v, L, R, B$  be as in Section 4.1 and Section 4.2. For simplicity, we assume that  $L = [a, e]$ . The value  $v$  is then the cardinality of the minimal representer set of  $[a, e]$ . From Remark 3, the total computation is  $O(\ell \times \max(\ell, \log k, v))$  exponentiations in  $\mathbb{G}$  and the total communication is  $O(\ell \times \max(\ell, \log k, v) |\mathbb{G}|)$  bits. Therefore, in order to reduce the computation and communication complexity, we need to reduce  $\ell$  and  $\max_k(\ell, \log k, v)$  by allocating  $k$ . Note that  $b, a, e$  take values from range  $[0, k^\ell]$  where  $k^\ell$  (setting  $z = k^\ell$ ) is fixed. Intuitively, we can reduce the value of  $\ell = \log_k z$  by raising the value  $k$  and therefore reduce the complexity. However, raising  $k$  will raise the value  $\log k$ . Furthermore, it is unclear how does  $v$  change when raising  $k$ . It is then needed to make sense how does  $v$  change.

We give some results for  $v$ .

**Lemma 5.** *Let  $R = \{r_1, \dots, r_t\}$  be the minimal representer of a set of leaf nodes in an  $\ell$  PKT. Let  $T_i$  be the coverage of node  $r_i$  for  $1 \leq i \leq t$ . Then  $T_i \cap T_j = \emptyset$  for  $1 \leq i, j \leq t$  and  $i \neq j$ .*

*Proof.* It is easy to verify that  $r_i$  is the minimal representer of  $T_i$ . Assuming that there exists a leaf node  $e \in T_i \cap T_j$ , then  $r_i, r_j$  both cover  $e$  and so one is an ancestor of the other, which is contrary to Lemma 1.

We first give a result for the case of  $a = 0$ , i.e.,  $L = [0, e]$ .

**Lemma 6.** *In an  $\ell$  PKT, the cardinality of the minimal representer set of  $L = [0, e]$  is  $\sum_{i=0}^n e_i$ , where  $e_i$  is the  $i$ th (from right to left) digit in the  $k$ -ary notation of  $e + 1$  and  $e_n \neq 0$ .*

*Proof.* Let  $R = \{r_1, \dots, r_t\}$  be the minimal representer of  $L$  and  $T_i$  be the coverage of node  $r_i$  for  $1 \leq i \leq t$ . Then, for  $1 \leq i \leq t$ ,  $r_i$  is the minimal representer of  $T_i$ . By Lemma 5,  $T_i \cap T_j = \emptyset$  for  $1 \leq i, j \leq t$  and  $i \neq j$  and then  $e + 1 = |L| = \sum_{i=1}^t |T_i|$ . Since the number of nodes covered by  $r_i \in R$  is of the form  $k^{\tau_i}$  for a definite nonnegative integer  $\tau_i$  by Definition 10, then  $e + 1 = \sum_{i=1}^t |T_i| = \sum_{i=1}^t k^{\tau_i} = \sum_{\tau_i, 1 \leq i \leq t} n_i k^{\tau_i}$ , where  $n_i$  is the times of  $k^{\tau_i}$  appeared in  $\sum_{i=1}^t k^{\tau_i}$ . By Lemma 2 there are at most  $k - 1$  nodes  $r \in R$  such that  $r.h = i$  for  $0 \leq i \leq \ell$ . Since each node  $r \in R$  covers  $k^{r.h}$  nodes in  $L$ , which says that each node at the same level in  $R$  covers the same numbers of leaf node, then  $0 \leq n_i \leq k - 1$ . Hence,  $\sum_{\tau_i, 1 \leq i \leq t} n_i k^{\tau_i}$  is the  $k$ -ary notation of  $e + 1$ . Therefore,  $|R| = \sum_{i=0}^n e_i = \sum_{\tau_i, 1 \leq i \leq t} n_i$ . The proof is complete.

We now give a result for  $L = [a, e]$ .

**Lemma 7.** *Let  $L, a, e$  be as above. Let  $a_t a_{t-1} \dots a_0$  and  $e_t e_{t-1} \dots e_0$  be the  $k$ -ary notations of  $a$  and  $e + 1$  respectively and let  $e_t \neq 0$ . Then*

1. if  $a_t < e_t$ ,  $|R_{[a,e]}| = (e + 1)_k + ((a_t + 1)k^t - a)_k - a_t - 1$ ,
2. otherwise (i.e.,  $a_t = e_t$ ),  $|R_{[a,e]}| = |R_{[a - a_t \times k^t, e - e_t \times k^t]}|$ ,

where  $R_{[x,y]}$  denotes the minimal representer of  $[x, y]$  in the  $\ell$  PKT and  $(x)_k$  denotes the sum of every digits in the  $k$ -ary notation of nonnegative integer  $x$ .

*Proof.* We separately prove the lemma in the case that  $a_t < e_t$  and the case that  $a_t = e_t$ .

If  $a_t < e_t$ , there exist two cases: the case that  $e_t = a_t + 1$  and the case that  $e_t > a_t + 1$ .

(a) If  $e_t = a_t + 1$ , then  $L = [a, (a_t + 1)k^t - 1] \cup [e_t k^t, e]$  while  $e > e_t k^t - 1$ , or else  $L = [a, e_t k^t - 1]$  while  $e = e_t k^t - 1$ . While  $e > e_t k^t - 1$ ,  $R_{[a,e]} = R_{[a, e_t k^t - 1]} \cup R_{[e_t k^t, e]}$ . By the symmetric property of PKT,  $|R_{[a, e_t k^t - 1]}| = |R_{[0, e_t k^t - a - 1]}|$  and  $|R_{[e_t k^t, e]}| = |R_{[0, e - e_t k^t]}|$ . Then  $|R_{[a,e]}| = |R_{[a, e_t k^t - 1]}| + |R_{[e_t k^t, e]}| = ((a_t + 1)k^t - a)_k + (e - e_t k^t + 1)_k = \sum_{i=0}^{t-1} e_i + ((a_t + 1)k^t - a)_k + (e_t - a_t - 1) = (e + 1)_k + ((a_t + 1)k^t - a)_k - a_t - 1$ . While  $e = e_t k^t - 1$ ,  $|R_{[a,e]}| = 1 = \sum_{i=0}^{t-1} e_i + ((a_t + 1)k^t - a)_k + (e_t - a_t - 1)$ .

(b) If  $e_t > a_t + 1$ ,  $L = \cup_{i=1}^{e_t - a_t - 1} [(a_t + i)k^t, (a_t + i + 1)k^t - 1] \cup [a, (a_t + 1)k^t - 1] \cup [e_t k^t, e]$  while  $e > e_t k^t - 1$ , or else  $L = \cup_{i=1}^{e_t - a_t - 1} [(a_t + i)k^t, (a_t + i + 1)k^t - 1] \cup [a, (a_t + 1)k^t - 1]$  while  $e = e_t k^t - 1$ . While  $e > e_t k^t - 1$ ,  $R_{[a,e]} = \cup_{i=1}^{e_t - a_t - 1} R_{[(a_t + i)k^t, (a_t + i + 1)k^t - 1]} \cup R_{[a, (a_t + 1)k^t - 1]} \cup R_{[e_t k^t, e]}$ . Then  $|R_{[a,e]}| = \sum_{i=0}^{e_t - a_t - 1} |R_{[(a_t + i)k^t, (a_t + i + 1)k^t - 1]}| + |R_{[a, (a_t + 1)k^t - 1]}| + |R_{[e_t k^t, e]}| = (e_t - a_t - 1) + ((a_t + 1)k^t - a)_k + (e - e_t k^t + 1)_k = \sum_{i=0}^{t-1} e_i + ((a_t + 1)k^t - a)_k + (e_t - a_t - 1) = (e + 1)_k + ((a_t + 1)k^t - a)_k - a_t - 1$ . While  $e = e_t k^t - 1$ , the conclusion can be proved similarly as the case (i).

If  $a_t = e_t$ , which says that  $(0, a)$  and  $(0, e)$  are both covered by the node  $(t, a_t - 1)$  in level  $t$ , then  $(t, a_t - 1)$  is an ancestor of all nodes in  $R_{[a,e]}$  and  $(t, a_t - 1) \notin R_{[a,e]}$ . (Otherwise, if  $(t, a_t - 1) \in R_{[a,e]}$ , then  $(t, a_t - 1)$  is the minimal representer of  $[a, e]$ . We have  $a = a_t k^t$  and  $e = a_t k^t + k^t - 1$  and so

$e + 1 = a_t k^t + k^t$ , which says that  $e_t = a_t + 1$ , a contradiction to  $a_t = e_t$ . Therefore,  $R_{[a,e]} = R_{[a-a_t \times k^t, e-e_t \times k^t]}$  and so  $|R_{[a,e]}| = |R_{[a-a_t \times k^t, e-e_t \times k^t]}|$ .

In all, the proof is complete.

We then have Theorem 3.

**Theorem 3.** *Let  $a, e$  be as above. Let  $a_t a_{t-1} \cdots a_0$  and  $e_t e_{t-1} \cdots e_0$  be the  $k$ -ary notations of  $a$  and  $e + 1$  respectively and let  $e_t \neq 0$ . Let  $s$  be the first integer  $i$  such that  $a_i < e_i$  for  $i$  from  $t$  to  $0$ . Then,  $|R_{[a,e]}| = \sum_{i=0}^s e_i + ((a_s + 1) \times k^s - \sum_{i=0}^s a_i \times k^i)_k - a_s - 1$ .*

From Theorem 3 we have Corollary 4.

**Corollary 4.** *Let  $a, e$  be as above. Then  $|R_{[a,e]}| \leq 2(k-1) \log_k e$ .*

By Theorem 3,  $|R_{[a,e]}| = \sum_{i=0}^s e_i + ((a_s + 1) \times k^s - \sum_{i=0}^s a_i \times k^i)_k - a_s - 1$  which displays that the minimal representer of  $[a, e]$  in an  $\ell$  PKT is determined entirely by the digits of the  $k$ -ary notations of  $e + 1$  and of “the complement of  $a$ ”. Hence, different  $k$  will result in different  $R_{[a,e]}$  and so different  $v = |R_{[a,e]}|$ . It is interesting that a larger interval may have a very small sizable minimal representer if we choose a suitable  $k$  (needs not to be large), e.g., when the weights of  $e + 1$  and of “the complement of  $a$ ”, i.e.  $(a_s + 1) \times k^s - \sum_{i=0}^s a_i \times k^i$ , are both small for  $k$ . Therefore, we should choose suitable  $k$  to reduce  $v$  and then to reduce the complexity of Protocol 2.

Recall that the total computation is  $O(\ell \times \max(\ell, \log k, v))$  exponentiations in  $\mathbb{G}$  and the total communication is  $O(\ell \times \max(\ell, \log k, v) |\mathbb{G}|)$  bits by Remark 3. We should choose suitable  $k$  to leverage the values of  $\ell, \log k, v$  to reduce the complexity of Protocol 2.

## 5 Conclusion

Protocol 2 gives an efficient and secure solution to the PIC problem. By choosing suitable  $k$ , we can further reduce the complexity of the protocol. This property is especially important in the location-based access control applications where resource is limited. Applying our protocol to the location-based access control applications would be one of our future works.

As stated in the paper, besides the PIC protocol, our work has a byproduct, i.e., a secure integer comparison protocol in the malicious model. It seems that the later protocol would have more future applications than the former, such as in electronic election, credential systems, electronic auction, etc.

Furthermore, we only commit to the input of Client, the integer, in Protocol 2. By considering fairness, it would be needed to extend the protocol to the case that both parties’s inputs, i.e., the integer and the interval, are committed which would be our another future work.

## 6 Acknowledgment

The research is supported by following funds: National Science and Technology Major Project under Grant No.2010ZX01036-001-002 & 2010ZX01037-001-002, and the Knowledge Innovation Key Directional Program of Chinese Academy of Sciences under Grant No.KGCX2-YW-125 & KGCX2-YW-174.

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