Maintaining Data Integrity in Fog Computing Based Critical Infrastructure Systems

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Abstract—The evolution of the utilization of technologies in nearly all aspects of life has produced an enormous amount of data essential in a smart city. Therefore, maximizing the benefits of technologies such as cloud computing, fog computing, and the Internet of things is important to manage and manipulate data in smart cities. However, certain types of data are sensitive and risky and may be infiltrated by malicious attacks. As a result, such data may be corrupted, thereby causing concern. The damage inflicted by an attacker on a set of data can spread through an entire database. Valid transactions that have read corrupted data can update other data items based on the values read. In this study, we introduce a unique model that uses fog computing in smart cities to manage utility service companies and consumer data. We also propose a novel technique to assess damage to data caused by an attack. Thus, original data can be recovered, and a database can be returned to its consistent state as no attacking has occurred.

Index Terms—Fog Databases, Malicious Transactions, Affected Transactions, Data Integrity

I. INTRODUCTION

The future of the internet is in the Internet of Things (IoT), evidenced by the significant increase in wearable technology, smart homes and buildings, connected vehicles, and smart grids. The number of connected IoT devices in use by 2025 is estimated at nearly 75 billion [1], producing an enormous amount of data predicted to total more than 79 zettabytes [2]. Limitations and restrictions in bandwidth, as well as this rapid growth in the amount of data produced, make the current information system architecture inadequate for managing and moving that volume of data to the cloud. In many scenarios, with increasing use of IoT devices, it would be impractical to do so. Additionally, contemporary society has incorporated a staggering number of sensitive and real-time IoT applications as integral parts of daily life. Connected car technologies, video conference applications, health monitoring, and real-time production line monitoring, are all applications requiring low-latency and location awareness in order to provide high-quality services for this technology-driven era [3].

IoT devices, such as smart meters in modern smart cities, will not only produce a massive amount of data, but heterogeneous data that will need to be processed in real-time [4]. This data will not be valuable enough without exploiting the maximum benefits from other technologies. It is unmanageable and nearly impossible for a cloud to handle the many tasks, of processing and aggregating, analyzing and storing for such volumes of disparate data [5]. For that reason, fog computing was presented by Cisco [6].

Fog computing is trending today because it has several unique characteristics that, not only establish it as an extension of the cloud, but also provide privileges in addition to, and complementing, those of the cloud. This complement to cloud computing, in an age of cloud processing, is significant in allowing the performance of resource, intensive, and extended term analytics [7].

In the potential for smart cities, fog computing will help the IoT and smart meter devices process the data and make quick decisions to take the right action within a critical timeframe and to aggregate only the indispensable data for the cloud. Services and utility companies, such as water and electric companies, can exploit fog computing technology to manage and analyze the volume of consumers data. There are many existing studies on how to expand the efficiency of fog computing in smart cities and to solve technical issues related to the large volume of data that needs fusion and integration to the cloud [8]. Moreover, while security and privacy issues have been addressed by many researchers, other aspects need more attention, such as a case in which a protection system fails during a cyberattack and customer data need to be recovered. This study aims to detect all transactions that are affected by any malicious transaction, recover the correct value of data, and ensure the integrity of consumer data in a fog computing environment in smart cities.

II. LITERATURE REVIEW

As a new network technology, fog computing has attracted many researchers. Quite a number of papers have presented a general survey or study of the challenges, issues, and future direction of fog computing [9]. Other works write about the architecture of the fog system [10]. Security and privacy issues are also a hot topic in this field [11], [12].

Many researchers have written about the use of fog computing in smart grids and cities to improve the quality of services provided to consumers and to solve security and privacy matters. Zhu et al. [13] proposed a new architecture for using fog computing in smart cities. They presented a privacy enhancement scheme that would use techniques such as blind
signature to provide anonymous authentication on consumer data. They also proposed applying extra encryption techniques on the smart meter readings of all consumer data at times. This can be done when each fog node is aggregated to the cloud. Although Zhu et al. claimed that their proposed scheme would enhance the privacy and security of consumer data, their model is still vulnerable to electronic and insider attacks.

Lyu et al. [11] proposed a new framework to securely aggregate smart meter readings through fog nodes and to the cloud. To ensure consumer data privacy, their data will be encrypted after adding some statistical noise using the Gaussian noise technique. Furthermore, Aazam et al. [10] discussed the architecture of the Industrial Internet of Things, which is the use of the IoT in the manufacturing industry for such applications as smart sensors, actuators, and robots. It is important for fog computing to be a solution that provides essential support closer to end users to ensure local and real-time processing for sensitive and complex tasks.

Much research has been conducted in the area of damage assessment and data recovery. Researchers have proposed models and mechanisms that try to recover data after cyber-attacks. The column dependency based approach introduced by Chakraborty et al. [14], observes the relationship between transactions to determine which transactions have been affected by malicious attacks and need to be recovered. In this way the time-consuming recovery of data after attacks will take less time than traditional approaches. Chakraborty et al. proposed a recovery method that will take the affected transactions as input and perform the recovery in two stages: compensation and re-execution. Their experiments indicated that when malicious transactions increase in the database, the second stage of their recovery scheme is also increased.

Liu [15] aimed to improve the efficiency of damage assessment and repair in distributed database systems. They first identified the challenges and complications that those systems face and then proposed an algorithm for distributed damage assessment and repair. On each site, they adopted a Local Damage Assessment and Recovery (DAR) Executor to scan the local log to detect and clean any sub-transactions that were affected by a malicious transaction. Also, on each site there is a Local DAR Manager that cooperates with the Executor to ensure global coordination between all sites on the system by generating a coordinator for any cleaning transaction.

Panda et al. [16] used the data dependency-based approach to assess the damage that could occur from electronic attacks and then to return the database to a consistent state. They introduced two algorithms. In the first one, damage assessment and recovery algorithms are executed at the same time, blocking the system until the whole procedure is complete and causing significant delays as a result. The second algorithm addresses the delays since the system should be available soon after all the affected and damaged data have been detected and blocked.

Alazeb and Panda [12] introduced two different models for using fog computing in a healthcare environment. The first model is an architecture that uses fog modules with heterogeneous data, and the second model uses fog modules with homogeneous data. For each model, they propose a unique methodology to assess the damage caused by malicious transactions so that original data may be recovered and affected transactions identified for future investigation.

III. Model

In this section, a unique architecture for using a distributed fog node system in smart cities to manage the consumer data of utility services will be proposed. Then, cooperative algorithms will be proffered for identifying, assessing, recovering, and restoring all the damaged and affected data created by an attack. The goal is the restoration of a reliable database. In the proposed model, it is assumed that the Intrusion Detection System (IDS) is responsible for detecting malicious transactions in the system and providing a list of those transactions to the damage assessment algorithms. Each fog node in the proposed architecture must have its own log file and use a strict serializable history. All operations in the log file need to be in the same order in the history. The log files cannot be user modified at any time. Since the log files will contain a record of every modification to the value of any data item that is updated by write operations, all read operations are also required to be stored in the log files to identify the data dependencies between the operations and the transactions and among the detections of the victim fog nodes in the systems.

A. Model Nations

A description of the notations to be used in the proposed model can be found in Table I.

| Notation | Description |
|----------|-------------|
| pub_fog | The public fog nodes that are accessed by customers and utilities providers. |
| use_fog | The private fog node for each utility service company. |
| MT_L | The list of detected malicious transactions done by IDS. |
| DA_Table | The damage audit table, which is a data structure that will be created by the damage assessment algorithms to collect data about transactions that are needed to do the data recovery, such as the valid and invalid read data items, data written, and accessed fogs. |
| DI_L | The damage item list that will contain all damaged data items that are identified by our proposed damage assessment algorithms. |
| DI_Fog_x | The Fog_x damage item table, where x is the ID of the secondary affected fog node, which reads any damage data item from another fog node. |
| VI_Fog_x | The valid data items table that will be created by algorithm 3 or 4 to add to it all recovered data items for the secondary affected fog node Fog_x. It will be sent to Fog_x to use it as input on algorithm 4. |
| w_i(A, v_1, v_2) | The write operation of the transaction T_i, v_1 is the before image, which represents the old value of the data item A before any updating. And v_2 is the after image, which is the new value of data item A after it is updated. |
| r_i(A, v) | The read operation of transaction T_i where A is the data item and v is the current value of A. |
B. The Proposed Architecture

In the proposed model, each smart city will have several public fog nodes (pub_fog), which will be efficiently distributed to guarantee the quality of service at each point of the entire city. Private fog nodes will be included, with at least one private fog node for utility service companies (usc_fog), such as water, electricity, and gas utilities. The usc_fog nodes should be effectively located in the center of the whole distributed system to ensure a reliable connection to all pub_fog nodes and provide different routes should one of the pub_fog nodes disconnect for any reason. Consumers will be able to send queries to pub_fog nodes only. Data may be retrieved from the local database if available there. Otherwise, the queries will be forwarded to the appropriate usc_fog node. Consumers are not allowed to directly connect the usc_fog nodes for security reasons. All queries related to those nodes will come through the pub_fog nodes. Customer utility usage data will be collected from smart homes and buildings using IoT devices and smart meters. Usage data will be sent to the nearest efficient pub_fog nodes based on several factors, such as location and load balance. It is assumed that each pub_fog node in the system will have the ability to perform some essential data operations, such as calculating customer average usage over a specific time frame or aggregating the totals of selected data values. Those operations are fundamental to optimization of the network bandwidth since the data sent over the network will be diminished by aggregating the necessary data. Additionally, as most customer data will be processed locally, at the edge of the network, it will enhance privacy and security by reducing sensitive data transmittal. Each utility usc_fog node receiving the data will also perform some essential computations, such as calculating the daily bill and average daily customer usage. These computations by the utilities are important in improving the quality of services in each city as the need for expansion of services in peak seasons may become evident and shortages avoided. Utilities may use data to plan fuel purchases or raise consumer awareness regarding consumption and conservation.

C. The Proposed Damage Assessment Algorithms

1) Algorithm 1: The Main Damage Assessment Algorithm:

The IDS is responsible for identifying the attacking transactions and sending a list of them to the victim fog node. Whenever one or more malicious transactions are found on any fog node in the system, the IDS will detect them and send them as a list (MT_L) to that fog node to be used as input in the proposed schemes. Once the fog node receives the list, it will launch Algorithm 1, which is the main damage assessment algorithm.

As soon as Algorithm 1 is launched, it will create the damage audit table (DA_Table) and damage data item list (DI_L). Both will be initialized to null. Then, the algorithm will scan the local log file of the victim fog node, Fog_x, beginning from the first attacking transaction of (MT_L) list, T₁. T₁ will be added as a new record into DA_Table since it is the first attacking transaction. If the attacking transaction updates at least one data item, then this data item will be damaged, and any other updating transactions that read this data will be affected as well. It is important to collect and store all data items that have been updated and damaged by the attacking transactions. Then, all transactions that have read those damaged data items can be identified, and data dependency can be declared between the transactions and the fog nodes in the entire system.

One of the main functionalities of this algorithm will be the collection of data before damage occurs, and store those images, which represent the pre-attack value of the data item, in the written data column on the DA_Table. These images will be used later in the recovery algorithm. Simultaneously, those damaged data items will be added to the damaged item list to determine data dependency.

Also, the algorithm will examine every transaction in the log file following, the first attack, to determine whether any other transaction is an attacking transaction, or a data access transaction from another fog node, or an updating write transaction. In the case where the transaction is an attacking transaction, the algorithm will perform as in the first attacking transaction. However, if the transaction is an access transaction from another fog node (Fog_y), the algorithm will check every data item that has been read by Fog_y. A new damage item table for Fog_y (DIT_Fog_y) will be created and all damaged data items that have been read by Fog_y as well as the transaction identification will be added to the DIT_Fog_y.

Since a fog node may access the same data multiple times, it is essential to know the transaction ID; this will make it easy to find on its log file and confirm that the damaged data items were not corrected later on in the fog node by valid updating.
Algorithm 1 The Main Damage Assessment Algorithm
1: Create a new DA_table and initialize to null
2: Create a new DL, and initialize to null
3: for every Ti, the local log starting from the first attacking transactions of MT, do
4:     if Ti is attacking transaction then
5:         add it as a new record into DA_Table
6:         for every wi (A, v1, v2) do
7:             add (A, v1) pair to data written column
8:             add A to the DL_L if it is not there
9:         else if Ti is transaction from another fog node x then
10:            for every data item A read by Ti do
11:               if A ∈ DL_L then
12:                   if DIT_Fogx does not exist then
13:                       Create a new DIT_Fogx where x is the ID of aimed fog node that reads the affected transaction
14:                       Mark Ti as affected transaction
15:                       Add Ti and A into DIT_Fogx
16:                       Update the last column of DA_Table
17:               else
18:               add it as a new record into DA_Table
19:         for every ri (A, v) do
20:             if A ∈ DL_L then
21:                 add A to invalid read column
22:             else
23:                 add (A, v) to valid read column
24:             for every wi (A, v1, v2) do
25:                 if invalid read column of Ti, ≠ ∅ then
26:                     add (A, v2) to data written column
27:                     add A to the DL_L if it is not there
28:                 else
29:                     check If (A ∈ DL_L)
30:                         add (A, v2) to data written column
31:                         delete A from DL_L
32:             if ci is found & (both invalid read and data written columns of Ti) = ∅ then
33:                 delete the record of Ti from DA_Table
34:             else if ai is found then
35:                 delete the record Ti from DA_Table
36:         Send DIT_Fogx to Fogx to do further detection
37:     Send DA_Table & DL_L for data recovery (algorithm 3)

the meantime, the DA_Table will be updated indicating that Fogx has read the damaged data item, so when the recovery algorithm has successfully corrected the value of the damaged data item, it will send the correct value to Fogx to use as input for its own recovery algorithm. If the transaction is an updating transaction (T_w), and not an attacking transaction belonging to the malicious transaction list, then it must be added to the DA_Table and examined to accomplish two goals. The first goal is to determine data dependency. All read operations must be checked to confirm whether T_w has read any of the damaged data items that already exist to the damaged item list. If so, those damaged data items will be added to the invalid read column of T_w, and undamaged data items will be added to the valid read column. Then, all the write operations will be checked to determine whether any have read damaged data items. If so, that means the damage has spread and the written data item is also corrupted. Therefore, it will be added to the damaged item list, if it is not already there.

However, if the transaction T_w updates any data item, (A), without reading any items from the damaged item list, then the data item (A) will be further checked evaluate its inclusion in the damaged item list. If (A) was updated without reading a corrupted transaction, that means it is a valid write and the data item (A) has been refreshed, so (A) must be removed from the damaged item list as in steps(28-30). The new value will be added to the data written column, accomplishing the second goal of adding the non-attacking updating transaction to the DA_Table.

Finally, all data items in the main victim fog node will be available for use except the damaged data items on DL_L. Therefore, system availability will be increased. The damage item table DIT_fogx will be sent to fogx to do further detection, while the damage audit table and damage item list will be sent to Algorithm 3, which is the main data recovery algorithm.

2) Algorithm 2: Secondary Fog Node Damage Assessment Algorithm: This algorithm will be like Algorithm 1, with some differences. The main difference in the input of this algorithm is the DIT_Fogx, which is one of the outputs of Algorithm 1 if an affected fog node reads any damaged data item from the main victim fog node. Assume Fogx is the main victim fog node in the system, and it was attacked and maliciously updated in the transaction T_i, which wrote the data item(Z). Later, Fogx accessed Fog1 via the transaction T_j to read (Z) and update other data items, (N) and (M), on its database. Here we call Fogx the secondary affected fog node. Once the secondary affected fog node in our example, Fogx, receives the DIT_Fogx containing (Z) as a damaged data item , it will create a new damage audit table and initialize it to null. Note that this algorithm will use the received DIT_Fogx to store and track the damaged data items instead of creating a new damage item list.

The algorithm will scan the log file and start from the first affected transaction from the received table. Therefore, whenever an affected transaction that belongs to DIT_fogx is found, the steps (3-12) will insert it as new record to the damage audit table and check each read operations if its belong to DIT_fogx, then add it to the invalid read column; otherwise, it will be added to the valid read column. Moreover, for the write operations, the updated data items along with its new values will be added to the data written column as well as they will be added to the DIT_fogx table if they are not there. In our example, data items N and M will be added to the DIT_fogx and the data written column in DA_Table. In a like manner, the damage item table, if there is one, will be sent to fogx while the damage audit table and damage item list will be sent to Algorithm 4, which is data recovery algorithm for the secondary fog node. The process continues until all the affected transactions in the entire system are detected.
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D. The Proposed Data Recovery Algorithms

1) Algorithm 3: The Main Data Recovery Algorithm

Immediately after Algorithm 1 has accomplished its task, it will send the DA_Table and DI_L to Algorithm 3 for data recovery. Once Algorithm 3 receives the DA_Table, it will scan the records that read invalid data items. When a data item record is found in the invalid read column, the algorithm will perform three steps:

- **Step 1:** Scan the data written column upward, beginning at the former record of DA_Table, for each data item (A) found in the invalid read column. Once the last updated and correct value of (A) is found, this value will be added as a pair (A, v) to the valid read column and data item (A) will be deleted from the invalid read column. This continues until all data items in the invalid read column in the same record have been recovered.

- **Step 2:** Recompute each data item in the data written column in the same record by reading the new values from the valid read column. Successful completion of Steps 1 and 2 should result in all data items in that record having the correct values.

- **Step 3:** Check the last column in the same record, which is the fog ID column, to determine if any data item has been read by another fog node in the system; if so, a new Valid Data Items table (VIT_Fog_x) will be created for each affected fog node. Then, the transaction ID along with the correct new value of each accessed data item will be added to the VIT_Fog_x.

As soon as all the records in the DA_Table have been examined and all three steps are successfully completed, the VIT_Fog_x will be sent to the corresponding fog node, Fog_x.

2) Algorithm 4: Secondary Fog Node Data Recovery Algorithm: This algorithm will be like Algorithm 3, with two primary differences. The first is that Algorithm 4 input will
be the DA_Table and the DIT_Fog_x from Algorithm 2 for the same fog node and the VIT_Fog_x from another fog node, Fog_1. Secondly, this algorithm will check every record on the received DA_Table. When a transaction that is marked affected is found, then for every data item (A, v) pair from the corresponding transaction on the VIT_Fog_x is copied to the valid data column on DA_Table and deleted from the invalid column of DA_Table. After all the damaged data items have been deleted on each record of the DA_Table, the data written column will be checked to discern if it is empty. If not, then the value v of each data item (A) in the data written column must be recalculated using the new values in the valid read column. However, the same procedure used in Algorithm 3 will be employed if the record has a transaction with some data items on the invalid read column. The process continues until all affected data items in the system are recovered to a consistent state.

E. An Example

To clarify the proposed scheme, consider the following example. There are two fog nodes in our smart city. Fog_1 is a pub_fog node collecting consumer data via smart meters. Fog_x is a private fog node used by the utility company to manage aggregated data and calculate consumer bills and consumption.

Consider the following log schedules for each one of them:

\[ S_{Fog_1} = r_1(A, 5) r_2(B, 4) w_1(C, 11, 9) w_2(G, 3, 9) r_3(B, 4) c_1 r_4(G, 9) w_3(A, 5, 13) w_4(D, 0, 13) c_2 r_5(G, 9) c_3 w_5(A, 13, 5) w_6(G, 9, 3) c_4 r_6(D, 13) r_7(A, 5) r_8(C, 9) w_7(D, 2, 27) c_5 r_9(B, 6) w_8(B, 4, 4) r_10(D, 16) w_9(D, 16, 20) r_11(A, 5) w_10(A, 5, 25) c_6 r_12(fog_1, T_1, D, 20) c_7 r_13(D, 9) c_8 w_11(C, 9, 11) c_9 r_14(A, 25) r_15(C, 11) w_12(E, 10, 36) c_{10} r_16(E, 36) c_{11} \]

\[ S_{Fog_2} = r_1(K, 3) r_2(fog_1, T_3, G, 9) w_3(K, 3, 12) c_9 r_4(K, 10) r_5(K, 12) w_4(M, 10, 22) c_{10} r_6(fog_1, T_5, D, 20) r_7(L, 4) w_8(N, 17, 24) c_{11} r_{12}(fog_1, T_1, L, 36) w_9(P, 4, 36) c_{16} \]

Now, suppose the IDS detects the first transaction, T_1, on the Fog_1 schedule is an attacking transaction and data items (C) and (G) are detected as having been maliciously updated. The IDS will send T_1 as the list MT_L to Fog_1. Once Fog_1, the primary victim fog node in the system, receives the list, it will launch Algorithm 1. Then, it will create a new DA_Table and a new DI_L. Consequently, the log file of Fog_1 will be scanned, beginning with the first attacking transaction on the MT_L, which is T_1.

Whenever an attacking transaction is found, such as T_1 in this example, it will be added to the DA_Table as a new record. All the write operations of T_1 will also be checked, so whenever a data item is found, it will be added along with its old value (before image) as a pair to the data written column, and the data items will be added to the damaged items list. In our example, the pairs (C, 11) and (G, 3) are added to the data written column (Table II) while the data items (C) and (G) will be added to DI_L. This will be the case for all attacking transactions that belong to MT_L.

The algorithm will examine the next transaction in the log file, which is T_2. Since T_2 is an updating transaction, it will be added into the DA_Table. Consequently, every reading operation in T_2 will be examined to ascertain if it read any damaged data item from the DI_L; if so, the data item will be added to the invalid read column, as apparent with (G). Otherwise, it will be added, as a pair with its value, to the valid read column. The next transaction is T_3. Fog_x has read the data item (G), which is a damaged data item. So, the Fog ID column will be marked and a new Damage Items Table will be created for Fog_x (DIT_Fog_x), adding data item (G) to the table with the transaction ID (Table III).

The algorithm will also find that damaged data items (A) and (G) have been refreshed in T_1 and updated without reading any other damaged data items. Therefore, they will be added, with their new values, to the data that were written and removed from the DI_L. The process continues until the end of the log is reached. Then, the DIT_Fog_x will be sent to

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**Algorithm 4 Secondary Fog Node Recovery Algorithm**

Once Fog_x receives the VIT_Fog_x

1. for each record in the DA_Table do
2. if T_i is affected transaction then
3. for every data item A in invalid read column do
4. copy the (A, v) pair from corresponding transaction on the VIT_Fog_x to the valid data column on DA_Table
5. delete A from invalid read column
6. if the data written column \(\neq \emptyset\) then
7. for every A in data written column do
8. recalculate the value of A using values in the valid read column
9. else if T_i is updating transaction & invalid read column \(\neq \emptyset\) then
10. for every A in invalid read column do
11. find the last updated (A, v) pair in data written column of DA_Table from the former records
12. add (A, v) to valid read column
13. delete A from invalid read column
14. for every A in data written column do
15. recalculate the value of A using values in the valid read column
16. if any fog_y is existing in fog ID column then
17. if VIT_Fog_y does not exist then
18. Create a new VIT_Fog_y where y is the ID of aimed fog node that reads the affected transaction
19. Add T_i and the (A, v) pair which is the correct value of A into VIT_Fog_y
20. Send VIT_Fog_y to Fog_y node
21. for every A in DIT_Fog_x do
22. check the new log that has just been created while the recovery process was in progress
23. if A is not modified in the log then
24. scan data written column of DA_Table upward to find last updated value of A
25. substitute the value of A in the database with v
Fog₂ to be used as input for Algorithm 2, while the DA_Table and DI_L will be sent to Algorithm 3, which is the primary recovery algorithm. All data items on DI_L will be blocked from being used until they recover.

Once Fog₂ receives the DI_TABLE, it will launch Algorithm 2 and use the DI_TABLE as input in further assessment and detection processes. Note that this table will add any damaged data items that are detected in Fog₂, (Table VII). Thus, a new DA_Table will be created. It will scan the local log of Fog₂, starting from the first affected transaction on the DI_TABLE, which is T₉. T₉ will be added to the new DA_Table and for every read operation, the data item will be examined to find out if it belongs to the DI_TABLE; if so, it will be added to the invalid read column. Otherwise, it will be added to the valid read column along with its value. Therefore, the data item fog₁.T₃.G will be added to the invalid read column, while the pair (K, 3) will be added to the valid read column (Table IV). However, it will do the same thing for the write operations as in Algorithm 1, so the updated data item (K) along with its value (K, 12) will be added to the valid written column.

Meanwhile, the data item (K), will be added into the DI_TABLE (Table V), since it becomes affected by reading the damaged data item fog₁.T₃.G. For T₁₀, the updating occurs after reading the damaged data item (K), so the scenario (the same as shown in T₂ in Fog₁) will be repeated (Table IV). Consequently, the process continues until the end of the log is reached. Once reached, the DA_Table for Fog₂ will be sent to Algorithm 4 to conduct data recovery. And all data items on Table V will be blocked until they recover.

As soon as Fog₁ has completed the damage assessment algorithm, Algorithm 1, and sent the DA_Table and DI_L to Algorithm 3 to proceed with data recovery, which will be launched immediately, and received the DA_Table and DI_L as inputs, it will scan the DA_Table from its beginning and search for any transactions that read invalid data items. For example, T₂ read invalid data item (G), and the algorithm looks for the last valid update value of (G), which must be the closest transaction before T₂. Therefore, T₁ must have the latest updated correct value of (G), which is (3). The pair (G, 3) will be copied to the valid read column, and (G) will be removed from the invalid read column. After that, T₂ will be recalculated using the new values (Table VI). (Note that in this example any transaction where write operations are found after read operations, all values of the read operations will be added together.)

Following T₂, T₃ will be processed in the same manner. As Fog₂ has read the damaged data item (G), a new Valid Data Item Table for Fog₂ (VIT_Fog₂) will be created and added to the transaction ID. T₃, and the correct value of (G), which is (G, 3) will be added (Table VII), and so on until the end of the DA_Table. After that, VIT_Fog₂ will be sent to Fog₂ to be used as an input in Algorithm 4 to recover the data.

Once Fog₂ receives the VIT_Fog₂, it will launch Algorithm 4 and use VIT_Fog₂ along with it is own DA_Table to process data recovery. Then, every record in the DA_Table will be checked. Since the first record, T₉ in this example, must be an affected transaction from Fog₂, then VIT_Fog₂ should have the correct and valid value of the damaged data item. Therefore, the new value of data item (G) will be copied from VIT_Fog₂ to the valid read column of the DA_Table and removed from the invalid read column. After that, T₉ will be recalculated using the new values (Table VIII). The rest of the algorithm will be almost the same as Algorithm 3.

### Table II
**The Damage Audit Table for Fog₁**

| T Id | Data written | Valid read | Invalid | Fog ID |
|------|--------------|------------|---------|--------|
| T₁   | (C, 11), (G, 3) |            |         |        |
| T₂   | (A, 13), (D, 13) | (B, 4) | G       |        |
| T₃   |            | G         |         | Fog₁   |
| T₄   | (A, 5), (G, 3) |            |         |        |
| T₅   | (D, 27) | (A, 5) | C, D   |        |
| T₆   | (D, 20), (A, 25) | (B, 4), (A, 5) | D |        |
| T₇   |            |            |         | Fog₁   |
| T₈   | (C, 11) |            |         |        |
| T₉   | (E, 36) | (C, 11) | A       |        |
| T₁₀  |            |            |         |        |
| T₁₁  |            |            |         |        |

### Table III
**Fog₁ Damage Item Table Created by Fog₁**

| Transaction Id | Damaged Data Items |
|----------------|--------------------|
| fog₁.T₁       | G                  |
| fog₁.T₂       | D                  |
| fog₁.T₁₁      | E                  |

### Table IV
**The Damage Audit Table for Fog₂**

| T Id | Data written | Valid read | Invalid | Fog ID |
|------|--------------|------------|---------|--------|
| T₁₀  | (K, 12) | (K, 3) | fog₁.T₂.G |
| T₁₄  | (M, 22) | (M, 10) | K       |
| T₁₆  | (N, 24) | (L, 4) | fog₁.T₇.D |
| T₁₈  | (P, 36) | | fog₁.T₁₁.E |

### Table V
**DI_TABLE for Fog₂ with all Damaged Data Items that are Found on Fog₂**

| Transaction Id | Damaged Data Items |
|----------------|--------------------|
| fog₁.T₁       | G                  |
| fog₁.T₂       | D                  |
| fog₁.T₁₁      | E                  |
| T₉             | K                  |
| T₁₀            | M                  |
| T₁₄            | N                  |
| T₁₆            | P                  |

### Table VI
**DA_TABLE for Fog₁ After Damaged Data Have Been Recovered**

| T Id | Data written | Valid read | Invalid | Fog ID |
|------|--------------|------------|---------|--------|
| T₁   | (C, 11), (G, 3) |            |         |        |
| T₂   | (A, 7), (D, 7) | (B, 4), (G, 3) |         |        |
| T₃   |            | (G, 3) |         | Fog₂   |
| T₄   | (A, 5), (G, 3) |            |         |        |
| T₅   | (D, 23) | (A, 5), (C, 11), (D, 7) |         |        |
| T₆   | (D, 27) | (B, 4), (A, 5), (D, 23) |         |        |
| T₇   |            | (D, 27) |         | Fog₂   |
| T₉   | (C, 11) |            |         |        |
| T₁₀  | (E, 43) | (C, 11), (A, 32) |         |        |
| T₁₁  |            | (E, 43) |         | Fog₂   |
Intrusion detection is one of the main phases that must be included to ensure the security and reliability of any computing system. This phase uses software or device to observe the system for any malicious activity or policy violation. However, detection systems sometimes fail to detect several malicious transactions on time, leading to data damage. Therefore, intrusion detection must be complemented by another phase, namely, damage assessment and data recovery, which ensures the integrity and availability of system data. This phase identifies any further affected transactions and ensures that the database returns to a consistent state. In this paper, we have introduced a novel architecture model for applying fog technology to smart cities. Working with the nature and characteristics of the model, we propose a unique method for assessing and recovering damaged data. As part of future work, we plan to evaluate the proposed model by simulating the whole environment and examining the performance of our algorithms.

**IV. CONCLUSION**

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