SECA: Snapshot-based Event Detection for Checking Asynchronous Context Consistency in Ubiquitous Computing

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Abstract—Context-consistency checking is challenging in the dynamic and uncertain ubiquitous computing environments. This is because contexts are often noisy owing to unreliable sensing data streams, inaccurate data measurement, fragile connectivity and resource constraints. One of the state-of-the-art efforts is CEDA, which concurrently detects context consistency by exploring the happened-before relation among events. However, CEDA is seriously limited by several side effects — centralized detection manner that easily gets down the checker process, heavy computing complexity and false negative.

In this paper, we propose SECA: Snapshot-based Event Detection for Checking Asynchronous Context Consistency in ubiquitous computing. SECA introduces snapshot-based timestamp to check event relations, which can detect scenarios where CEDA fails. Moreover, it simplifies the logical clock instead of adopting the vector clock, and thus significantly reduces both time and space complexity. Empirical studies show that SECA outperforms CEDA in terms of detection accuracy, scalability, and computing complexity.

I. INTRODUCTION

Ubiquitous computing aims to create intelligent environments saturating with computing and communication capabilities such that people access ubiquitous applications without knowing underlying technologies. This intelligence is mainly achieved by context-awareness, which assists ubiquitous applications in adapting to changeable contexts [1]. Contexts refer to pieces of information that captures the features of ubiquitous computing environments [2]. The checking of context consistency is fundamental to ubiquitous computing. For example, a RFID-based system may acquire two different locations of a user at the same time [3]. This kind of context consistency must be checked. However, contexts are often noisy owing to the unreliable connectivity and resource constraints [4]. Moreover, contexts frequently keep evolving with user mobility and situations [5, 6]. Therefore, the detection of context consistency is a non-trivial problem.

A variety of schemes for checking context consistency have been proposed. In [7, 8, 9], context consistency was specified by ontology assertions such that it could be checked by hidden rules and axioms from ontology. In [10, 4], context consistency was modeled by tuples and resolved by drop-all and drop-best policies without delineating the checking context consistency. In [11], a tree-based checking scheme based on the first-order logic was reported that checked context consistency by refining consistency trees using partial context constraints. However, most existing schemes are seriously limited by two problems. One is that they are centralized, which incurs their unscalability in large-scale ubiquitous environments with a huge number of nodes. The other is that they fall short when counting in temporal relations among context events, since they implicitly assume that contexts being checked belong to the same snapshot. But this assumption cannot be always held in ubiquitous computing environments that are characterized by asynchronous cooperation and schedule.

To remove the above assumption, CEDA [2] was proposed. It mapped the context consistency checking into context event detection, and checked concurrent context events based on the happened-before relation. However, CEDA suffers from three drawbacks, as shown in our previous work [12]. Firstly, it checked event detection in a centralized manner, incurring its less effectiveness in large-scale ubiquitous applications. Secondly, it introduced false negative because happened-before relation cannot accurately capture all event relations. Finally, CEDA suffered heavy space and time complexity, which led to its poor performance.

To this end, we propose in this paper SECA – snapshot-based event detection for context consistency checking, which is built on top of time snapshots and logical clocks. SECA detects context consistency in a distributed manner, which enables the checking nodes not to be blocked or become system bottle-necks. It adopts logical clocks instead of vector clocks to evaluate event relations. To be scalable, SECA customizes logical clocks by holding the value part. Thus, it detects event relations that CEDA can and cannot. Theoretical analysis and extensive experimental results show that SECA achieves higher detection accuracy than CEDA in a more scalable manner. The main contributions of this paper are three-fold.

- First, SECA removes the limitation held by CEDA that central-based checking systems are easily to get heavy computing load. In contrast, SECA achieves its function in a fully-distributed manner, which is highly desirable
in large-scale mobile ubiquitous computing.

- Second, SECA is capable of detecting false negative scenarios where CEDA fails by introducing the snapshot timestamp.
- Finally, SECA respectively reduces CEDA’s complexity of time and space for handling an event from \(O(n^2)\) to \(O(n)\) and from \(O(n)\) to \(O(1)\), where \(n\) is the number of nodes in ubiquitous network.

The remaining of this paper is structured as follows. Section II presents the design of SECA, followed by theoretical analysis. Section III reports our extensive experimental results. Section IV concludes the paper with a summary and the future work.

II. SECA: Snapshot-based Event Detection for Checking Asynchronous Context Consistency in Ubiquitous Computing

Generally, ubiquitous computing environments are modeled as a loosely-coupled distributed system, where physical entities (e.g., objects and users) sense environments, and ubiquitous infrastructures handle sensed data and deliver services to ubiquitous applications. In the following, we start with introducing our system formulation.

A. System Formulation

Suppose \(P_1, P_2, \ldots, P_n\) be \(n\) asynchronous processes in a ubiquitous computing environment, \(E_i\) be an event set in process \(P_i\), and \(lo\) and \(hi\) be the start and end of an event, respectively. Thus the event \(E_i\) is modeled as an interval. Note that processes communicate with each other only by means of message-passing, and the communication delay is finite but unbounded.

In this subsection, we first introduce the concept of snapshot timestamp and its update policy, and then reshape the happened-before relation with the snapshot timestamp.

Snapshot Timestamp. It refers to an implementation of the logical clock, where all nodes maintain a logical clock. In the system of snapshot clocks, the time domain is denoted as a set of \(n\) - dimensional and non-negative integer clocks. Each process \(P_i\) maintains a snapshot clock \(S_i = \{S_i[k]|k = 1, \ldots, n\}\), where \(S_i[k]\) is the \(k\)th local logical timestamp and describes the logical time progress at \(P_i\). The process \(P_i\) updates its snapshot clock by Rules 1 and 2.

1) Before sending a message, the process \(P_i\) updates its local clock by

\[
S_i[k] = S_i[k - 1] + d(d > 0), \tag{1}
\]

where the default value of \(d\) is 1. Then, the process \(P_i\) piggybacks a message \(m\) with its snapshot clock to the remaining nodes in the same environment.

2) When receiving a message \((m, S_j[send])\) from the process \(P_j\), the process \(P_i\) gets the snapshot timestamp at a receive point as:

\[
S_i[receive] = \max(S_i[k], S_j[send]), (1 \leq k \leq n) \tag{2}
\]

Figure illustrates the update policies of our snapshot clock algorithm, where events are represented by the start and end of intervals — i.e., \(lo\) and \(hi\). When the process \(P_i\) would like to send a message, it will automatically increment the value of its snapshot clock, and then delivers the message to the processes \(P_1\) and \(P_2\).

Evidently, by comparing timestamps (i.e., an array of \(n\) elements), the snapshot clock keeps its property of isomorphism. The relations between timestamp intervals include two ordering relations represented as ‘\(\leq\)’ and ‘\(<\)’, and one concurrent relation denoted as ‘\(\parallel\)’.

Property 2.1: Given two timestamp intervals \(Ip\) and \(Iq\) (a timestamp interval may contain a number of logically continuous timestamps), the isomorphism of the snapshot clock is given as:

\[Ip \leq Iq \iff \forall i, i' \quad Ip[i] \leq Iq[i']\]
\[Ip < Iq \iff Ip \leq Iq \text{ and } \exists i, i' \quad Ip[i] < Iq[i']\]
\[Ip \parallel Iq \iff \text{not} (Ip < Iq) \text{ and not} (Iq < Ip)\]

Snapshot-based happened-before relation. Let ‘\(\to\)’ denotes the happened-before relation, the snapshot timestamps based events in a distributed system satisfy Theorem I.

Theorem 1: Given two events \(b\) and \(c\) with respective timestamp intervals \(I_b\) and \(I_c\), then:

\[b \to c \iff I_b < I_c\]
\[b \parallel c \iff I_b \parallel I_c\]

Proof: According to the update policies of snapshot clocks, the happened-before relation is held.

Thus, an isomorphism exists between the partially ordered events produced by a distributed computation and their timestamps. This is a powerful and interesting property of snapshot clocks. Note that the happened-before relation between these two events is stated as \(b \to c \iff I_b < I_c\).

In order to easily detect concurrent events, we propose an event concurrence detection mechanism shown as Theorem 2.

Theorem 2: Given two events \(b\) and \(c\) in processes \(P_i\) and \(P_j\). Assume the event \(b\) sends a message to the event \(c\) with its timestamp \(I_b, x\), then:

\[b \parallel c \iff (I_c, lo \leq I_b, x < I_c, hi)\]

Proof: There is a message from the event \(b\) to the event \(c\). According to the update policy of snapshot clock, the value of \(I_b, x\) is not less than \(I_c, lo\). Meanwhile, the message is handled...
by the event $c$, indicating that the value of $I_b.x$ must be less than $I_c.hi$.

**B. Snapshot-based Concurrent Event Detection**

In this paper, we propose a SECA scheme — snapshot-based event detection for checking asynchronous context consistency in ubiquitous computing. SECA is built upon the top of the snapshot timestamps, and enables all nodes to detect concurrent context consistency events without central control or a centralized hierarchy. In SECA, the basis of context consistency detection is Theorem 2 and happened-before relation. Figure 2 illustrates the fact that the events $b$ and $c$ are concurrent, which is checked by Theorem 2.

The pseudo-code of SECA scheme is given as Algorithm 1, consisting of three parts: event processing, message processing, and context consistency checking. The event processing refers to a process that updates its snapshot clock when an event occurs within its life span. To be specific, the process updates its snapshot clock, the event queue $EQ$, as well as interval queue $IQ$ by broadcast (e.g., SECA offers a System-Broadcast primitive). When events communicate with messages, the processes where the events happen meet two types of message processing — sending and receiving. The sender is in charge of updating the event queue and interval queue (see steps 11-14). Correspondingly, the receiving process modifies its snapshot clock by picking the maximal timestamp value between the snapshot timestamps of the sender and receiver processes (see steps 15-19). Note that the actions of senders and receivers are incorporated together in the pseudo-code. The third part refers to the context consistency detection. Since elements in $EE$ implicitly satisfy Theorem 2, we output the event pairs simply by a validation check.

**C. Discussions**

Thus far we have presented the design of SECA. However, does SECA scheme solve false negative caused in CEDA scheme? Can SECA scheme detect context consistency accurately in ubiquitous computing environments? We investigate these issues by theoretical analysis in this section. Specially, we will study the false negative, complexity and implementation manner of the proposed scheme. Moreover, in the following Section III, we further evaluate SECA by extensive experiments.

![Fig. 2. Concurrent events $b$ and $c$, where $I_c.lo \leq I_b.x < I_c.hi$.](image)

**Algorithm 1: SECA checks context consistency in normal processes**

**Input:** $P = \{P_1, \ldots, P_i, \ldots, P_n\}$, a process set in a ubiquitous system

- $EQ[]$, an event queue;
- $IQ[]$, an interval queue;
- $EE[]$, pairs of events which have communication with each other;
- $S[]$, a list of snapshot timestamps;

**Output:** A set of concurrent events $C = \{<e_x, e_y>\}$

```
begin
    /* When an event $e$ occurs at $P_i$ */
    if $P_i$ occur $e$ then
        /* suppose it occurs at timestamp $k$ */
        with id $e_id_i$
        $S_i[k]=S_i[k]+1$;
        $EQ[j].push(e_id_j, S_j[k])$;
        $IQ[i].push(e_id_i, lo=S_i[k], hi=S_i[k]+1)$;
        System_Broadcast($P_i, S_i$);

    /* Upon the process $P_i$ receives a message from the process $P_j$ */
    if $P_i$ msg $P_j$ then
        ($e_id_j, S_j[k]$) = $EQ[j].getTop()$;
        $S_i[k+1]=S_i[k]+1$;
        $EQ[j].push(e_id_i, S_i[k+1])$;
        $IQ[i].push(e_id_i, lo=S_i[k], hi=S_i[k]+1)$;
        $S_i[receive] = max(S_i, S_j[k]+1)$;
        if $e_id_i$ is received by $e_id_j$ then
            ($e_id_i, lo, hi$) = $IQ[j].pop()$;
            $IQ[i].push(e_id_i, lo, max(hi, S_j[k+1]))$;
            EE.push($e_id_i, e_id_j$);

    /* Context consistency detection */
    while (!EE.isEmpty()) do
        <$e_id_i, e_id_j$> = EE.pop();
        if (isValid($e_id_i$) && isValid($e_id_j$)) then
            $C.push(e_id_i, e_id_j)$;
        /* Output concurrent events */
        Unique($C$);
```

1) **False Negative in happened-before-based Context Consistency Detection:** Given $n$ intervals $I_1, I_2, \ldots, I_n$, CEDA checks concurrent context consistency events by Eq. 3 which is built on top of happened-before relation. The case of interval overlaps which is characterized by concurrent events shown as Fig. 3. However, for some concurrent events whose intervals are overlapped, the CEDA scheme fails to detect them, which is notorious for false negative phenomena. This is because Eq. 3 cannot detect these overlapping intervals although they are mutual across.

\[ (I_j.lo \rightarrow I_k.hi) \land (I_k.lo \rightarrow I_j.hi), \forall 1 \leq j \neq k < n. \] (3)
CEDA scheme fails to check context consistency correctly. In relation in CEDA scheme, overlapping intervals that can be detected based on Figs. 5(a), 4(c) and 4(c), two events in two respective processes satisfy of senders with the successfully identifying these concurrent context events. As for Eq. 3 are blind of them. On the contrary, SECA is capable of (tion and computation capabilities. With respect to the hand-

Figure 4 illustrates three false negative scenarios where CEDA scheme fails to check context consistency correctly. In Figs. 4(a), 4(c) and 4(c), two events in two respective processes satisfy \((I_j,lo \rightarrow I_k,hi) \land (I_k,lo \rightarrow I_j,hi)\), \((I_j,lo \rightarrow I_k,hi) \land (I_k,lo \rightarrow I_j,hi)\), and \((I_j,lo \rightarrow I_k,hi) \land (I_k,lo \rightarrow I_j,hi)\), respectively. These two events concurrently take place, but Eq. 3 are blind of them. On the contrary, SECA is capable of successfully identifying these concurrent context events. As for Figs. 4(a) and 4(b), SECA compares the message timestamp of senders with the \(lo\) and \(hi\) of the receivers and then locates the concurrency. Note that concurrency in Fig. 4(c) is challenging to detect. This kind of concurrency is mainly caused by message delay. Owing to the space limitation, we only report the experimental results about how message delay affects the SECA performance, and omit the part of theoretical analysis.

2) Complexity: Taking a panoramic view of the SECA scheme, it is easy to find that SECA does not rely on central control to check context consistency. All processes involved in a ubiquitous system are equal and check context consistency by snapshot clocks. Every process requires \(O(1)\) space complexity to maintain snapshot timestamps, and \(O(n)\) time complexity for every context consistency event detection. Considering that many ubiquitous devices are with limited computing and communication capabilities, SECA is highly desirable with respect to efficiency and scalability in large-scale mobile ubiquitous environments.

To further evaluate the time and space complexity of the proposed scheme, we have implemented the detection schemes by physical clocks, vector clocks and snapshot clocks, labeled as PCA, CEDA and SCA schemes, correspondingly. Table 1 compares the PCA, CEDA and SCA in terms of clock synchronization, handling the occurrence of an event, detecting overlapped intervals and concurrent events, and false negative. By comparison, SCA significantly alleviates the time and space complexity concerning event processing and context consistency checking. Meanwhile, SCA also cuts off a half possibility of false negative generated in CEDA scheme.

3) Implementation Manners: In general, SECA scheme can be achieved in a distributed manner, the same as that of happened-before relation implementation in distributed systems. This kind of implementation is appropriate to PCs and supercomputers that are equipped with powerful communication and computation capabilities. With respect to the hand-held and embedded devices, e.g., sensors, RFID, and mobile phones, the proposed scheme can be reached by agents, e.g., mobile agents for RFID and mobile phones [13].

III. EXPERIMENTS

We conduct extensive experiments in this section to further evaluate whether SECA is appropriate to context-aware applications in asynchronous ubiquitous computing environments. In particular, this section will evaluate how the detection accuracy of SECA is, and whether SECA outperforms CEDA regarding detection accuracy and computation cost.

A. Experiment Setup

A smart building scenario is simulated where users move around. The duration of users’ stay in an office follows the exponential distribution. In view of that user location is regarded as the most important type of contexts in asynchronous ubiquitous computing environments [4], [14], [15], the user location is our focus. The holistic study environment is equipped with RFID devices and every user carries a RFID tag such that the location context is collected timely. The RFID data concerning user location is generated with controlled error rates of 10%, 20%, 30%, 40% and 50% by leveraging on the mechanisms provided in the existing literature [11], [16]. A constraint is implanted into the location context that a user cannot have two difference locations at the same time.

B. Overall performance

A series of experiments is designed to check the detection accuracy of SECA and whether it performs better than CEDA. Given that the experiments shed light on detecting concurrent events of user locations, we limit the number of nodes attending for the same contexts from 2 to 20. Every node runs two detection process instances. Every event has a random life span from 20 milliseconds to 50 milliseconds and every message suffers a random delay between 0.25 to 8 seconds. All experimental results are gained by PC equipped with Windows Enterprise 7 (32-bit), CPU 1.67GHz, and RAM 2GB. The following experiments share the same settings without explicit declaration.

Figure 5(a) illustrates the performance results with tuning the number of nodes from 2 to 20. Both CEDA and SECA schemes achieve a high level of detection accuracy of context consistency events, showing a slightly downward trend. This indicates that vector clocks and happened-before relation is efficient for detecting concurrent context consistency events. Meanwhile, SECA scheme acquires a higher level of accuracy.
than CEDA. This is because SECA correctly solves part of cases where CEDA gets false negative errors.

C. Detection performance with varying message delays

Several experiments are conducted to investigate how the message delay affects the concurrent event detection of the proposed scheme.

As shown in Fig. 5(b), detection accuracy of both SECA and CEDA schemes reduce their accuracy as the increase of message delay. In all experiments, SECA achieves a higher level of accuracy than CEDA owing to its snapshot-based timestamp checking mechanism. Especially, when the logarithm of the message delay is between -2 and 3, SECA gets a better detection accuracy with less communication overheads. Taking into account the scale of ubiquitous network, we hereby set the value of message delay as 0.25 to 8 milliseconds.

IV. CONCLUSION

In this paper, we have studied concurrent event detection for checking context consistency in asynchronous ubiquitous environments. We have proposed the snapshot timestamp and based on it we have put forward the SECA scheme, which reduces the time complexity of CEDA from \(O(n^2)\) to \(O(n)\), and the space complexity for handling an event from \(O(n)\) to \(O(1)\), where \(n\) is the scale of ubiquitous network. Extensive experimental results show that SECA is desirable in context-aware applications and outperforms CEDA regarding concurrent event detection accuracy, and robustness on message delay and event duration.

Currently, SECA scheme could be further improved in the following perspectives. Firstly, we need to investigate how SECA performs in large-scale ubiquitous computing environments with over ten thousands of participants. Secondly, we will study whether and how SECA copes with the dynamic changes of processes involved in the concurrent event detection. Finally, we plan to evaluate SECA in various scenarios with more types of contexts and consistency constraints.

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