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A virtual replica node-based flash crowds alleviation method for sensor overlay networks☆

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ABSTRACT

The rapid development of sensor networks has made it possible to build large-scale sensor overlay networks by integrating separated sensing resources. In our previous work, we employed a range queriable P2P (peer-to-peer) network, Skip Graph, as the overlay substrate of sensor overlay networks. Range queriable P2Ps such as Skip Graph enable retrieving sensing resources whose properties are within the specified range in an effective and scalable manner. A side effect of the range queriable property is that when flash crowds occur, it is likely that multiple nodes with successive keys/IDs will become hotspots at virtually the same time, which rarely happens in typical DHT (Distributed Hash Table)-based systems. In this work, we present a virtual replica node-based approach to protect sensor overlay networks from flash crowds. In the proposed approach, a hotspot node can request physically spare nodes located anywhere in the overlay to generate virtual nodes with its key and force the virtual replica nodes to join the overlay network as if they were normal nodes around the hotspot. The proposed method is effective for both single hotspot and hotspot zone scenarios. With theoretical analysis, simulations, and testbed experiments, we demonstrate that the proposed method is efficient, scalable and feasible.

1. Introduction

The explosive growth of sensors in the environment is enabling many future applications and services. To fully exploit the potential of sensing resources requires a feasible architecture to integrate separated sensing resources that are managed by different organizations. As a sensor network integration infrastructure, researchers widely accept connecting the gateways or base stations with a flexible overlay middleware that can hide the differences among different sensing resources. This kind of infrastructure can be referred to as sensor overlay network.

Recently, sensor overlay networks with range queriable P2Ps as an overlay substrate have attracted interest because range queriable P2Ps such as Skip Graph (Aspnes et al., 2007) enable the retrieval of sensing resources using their properties (Desnoyers et al., 2005; Teranishi, 2009; Takeuchi et al., 2014; Shao et al., 2014, 2015a,b). In our previous work, we developed a sensor overlay network based on Skip Graph as presented in Fig. 1 (Teranishi, 2009; Shao et al., 2014, 2015a,b). The right side of the figure illustrates the architecture of one overlay node. An overlay node must contain at least three components: sensing resource, sensor data storage and computing resource. The storage is used to store the real-time sensing data, and the computing resource is used to process the data, receive requests from the users, and make responses. Users can be machines, end users, IoT (Internet of Things) service operators and even other sensor overlay nodes. In practice, owners of sensing resources can implement this architecture easily with smart gateways, cloud computing and fog computing technologies (Aazam and Huh, 2014; Bonomi et al., 2012; Shaukat et al., 2016; Gai et al., 2016; Liao et al., 2015; Mor et al., 2016; Martella et al., 2014; Silva et al., 2014; Satyanarayanan et al., 2015; Xu and Helal, 2016; Zhang et al., 2015; Abdelwahab et al., 2016; Iera and Morabito, 2015; Manzalini and Crespi, 2016). The left side of the figure is a sensor overlay network developed by integrating separated sensor overlay nodes. The numbers near the gateways present a certain property of the sensing resources. The left lower part of the figure indicates the overlay substrate based on Skip Graph. Skip Graph is a structured P2P for efficient key retrieval. It is different from DHTs in that it enables both exact-match query and range query. Range query is an important functionality as it allows users to locate sensing resources without knowing their exact unique ID or IP address. For example, if an earthquake occurs in a specific area, users can locate the sensing resources they require with a query condition such as “sensors in the

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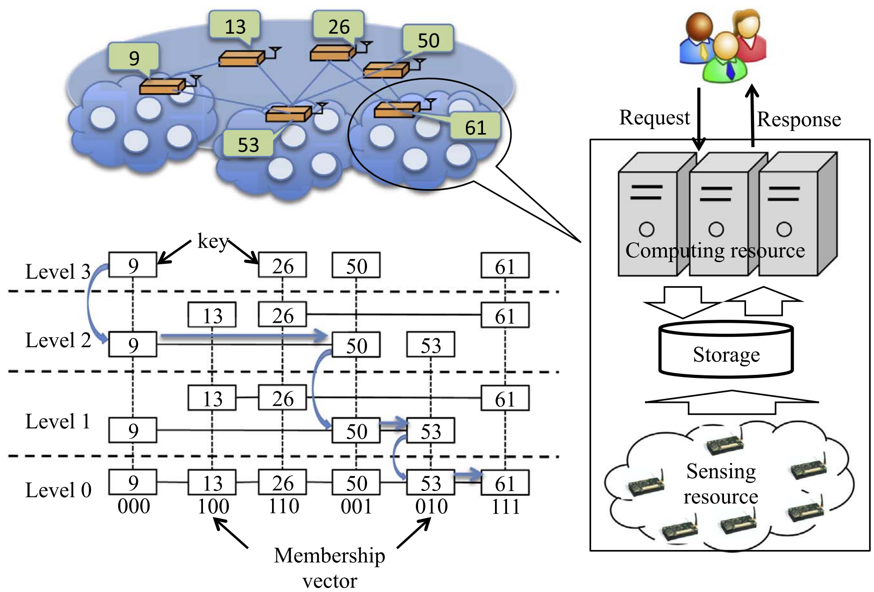

Fig. 1. An example of a sensor overlay network based on Skip Graph.

area within 100 km of the epicenter". Using range queriable P2Ps, more complicated and flexible requests can be realized. For example, the authors of Desnoyers et al. (2005) have indexed the sensor data in separated gateways with Interval Skip Graph, which enables range queries with the time interval of the data. In Takeuchi et al. (2014), the authors implemented a topic-based pub/sub system with Skip Graph. In their system, a topic was selected as a key and nodes that were interested in similar topics were neighbors of the overlay network; this is inherently guaranteed by Skip Graph. In Section 3, we introduced the functionality of Skip Graph in further detail..

Although sensor overlay networks based on range queriable P2Ps have proven to be effective in many scenarios, the overlay nodes suffer from flash crowds. A flash crowd can be characterized by a dramatic increase in requests for a service over a relatively short period (Jung et al., 2002). The damage caused by flash crowds to sensor overlay networks is quite serious mainly for two reasons. The first is related to the distributed and heterogenous nature of the physical resource. Sensor overlay nodes can be normal PCs, virtual machines (VMs) of a cloud data center, or fog computing sites. Regardless of the type, the single node does not have the computing and storage resource of high-end servers and clusters. Moreover, flash crowds always happen unpredictably; hence, it is impossible to over-provision the requirements for a physical resource. The second reason is associated with the key-order preserving property of range queriable P2Ps. If flash crowds occur, it is likely that several neighboring nodes will become hotspots simultaneously. Consider that if a key represents the position of a sensing resource, when an earthquake occurs, it is likely that the majority of the nodes around the epicenter will become hotspots. We call hotspot nodes with continuous keys a hotspot zone. A hotspot zone eliminates the possibility of alleviating flash crowds by pushing the contents and processes to neighbors as is implemented for DHTs (Bosneag et al., 2004; Rao et al., 2010; Qu and Xiong, 2012).

The proposed method to alleviate flash crowds for sensor overlay networks is based on an observation that when flash crowds occur, the majority of the nodes are spare except the hotspots and their neighbors. This observation inspired us to explore the use of the physical resource of the spare nodes. In the proposed approach, when a node identifies a flash crowd, it identifies and requests the qualified spare nodes to create virtual replica nodes with its key. The virtual replica nodes are then inserted into the overlay network as if they were normal nodes. According to the key-order preserving property, all the virtual nodes are inserted around the hotspot node in the overlay topology. The virtual nodes perform the same processes and provide the same service to the users as the hotspot node. With this approach, not only the request service load of the hotspot but also the request routing load of the hotspot's nearby nodes can be effectively distributed. As an added benefit, the proposed method can also reduce the average retrieval hop count significantly. This method is effective for both single hotspot and hotspot zone.

As we introduce multiple virtual replica nodes to behave in the same manner as the hotspot node, consistency maintenance is important. Further, although each of the virtual replica nodes share virtually the same portion of the request service load, the load balancing is probabilistic and skewness always exists. In some cases, the system may have to balance the load more precisely. Both of these tasks are challenging because it is not feasible and scalable to allow the hotspot node to manage all the virtual replica nodes in a centralized manner. In this work, we present a distributed virtual replica node tree (VRNT) with the hotspot as root and the associated virtual replica nodes as internal and leaf nodes to address these tasks. By exploiting the Skip Graph topology, the VRNT can be built and maintained easily with lower cost than similar approaches in DHTs (Chen et al., 2005; Hu et al., 2010; Shen and Liu, 2012). Considering VRNT as a multicast tree, the consistency maintenance can be achieved with multicasting. Moreover, by utilizing VRNT, we realize load rebalancing among the virtual nodes with specified precision in a distributed manner.

Range queriable P2Ps have several beneficial features; hence, we selected Skip Graph as the overlay substrate of the proposed sensor overlay network. However, we have found that range queriable P2Ps have not been paid as much attention as DHTs. To the best of our knowledge, this work is the first to analyze the essential differences between range queriable P2Ps and DHTs that prevent DHT-oriented flash crowd alleviation methods from performing effectively for range-queriable P2Ps. In this paper, we present the first range queriable P2P-oriented flash crowds alleviation method. Although the proposed work is based on Skip Graph, we claim that it can also be applied to the other range queriable P2Ps such as Mercury and Chord# (Schütt et al., 2008).

The remainder of this paper is divided as follows: in Section 2, we introduce some related research on sensor overlay and flash crowds alleviation. In Section 3, we provide a brief introduction of Skip Graph. Section 4.1 presents the proposed flash crowd alleviation method in detail. In this section, we also provide extensive simulation results to evaluate the related properties of the proposed method. In addition to