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Mobility-Aware Fog Computing in Dynamic Environments: Understandings and Implementation

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ABSTRACT Fog computing is an epitome to enable provisioning resources and services beyond the cloud, at the edge of the network, and nearer to end devices. Fog computing is not a counterfeit for cloud computing but a persuasive counterpart. However, the mobility of end users and/or fog nodes brings a major dilemma in the implementation of real-life scenarios. Therefore, we deliver the state-of-the-art research about mobility in fog computing. By identifying the mobility problems, requirements, and features of different proposals, we discover the open problems from subsisting studies and summarize the advantages of mobility for readers. This will help the researchers and developers avoid the current misapprehensions and capture the real-life scenarios, such as business, government, and education institutions. In spite of the extensive state-of-the-art research work, we also present the diverse mobility factors to investigate the correlation between dynamic nodes with fog nodes in order to accomplish better successful tasks. We conceive that the investigations of mobility factors in the fog computing will furnish the novel perspective on not only dynamic connections but also network dynamics. To revolutionize the follow-up research, we distinguish and foreground futurity directions concerning real-life scenarios of people and vehicles in a dynamic fog environment.

INDEX TERMS Fog computing, edge computing, cloud computing, mobility, mobility environments, mobility factors, performance.

I. INTRODUCTION

In the last decade, due to the exponential growth of mobile internet traffic, the attractiveness of mobile devices have been directing the remarkable development in wireless communication and networking [1]. Particularly the revolutions in small cells based heterogeneous networks, massive MIMO and mm-Wave communications cater users gigabit wireless access in next generation [2]. Therefore, the remote cloud data centers have high processing power and large memory storage that enables low processing mobile devices to run their respective computing services. However, cloud computing has certain limitations. For instance, the data generation and consumption can be occurred at diverse applications, users' locations, interaction time and response time. Applications such as video calls, voice and online gaming are highly affected by users' movement and locations. This leads to higher latency, processing and storage requirements, and such problems varies across applications. In this new era, the users' requirement of lower latency, lower processing and storage may not be suitable for applications relying on cloud computing due to static condition of cloud, and long distance between cloud-servers and end-users. Additionally, the data execution of different applications does not take user mobility into consideration in cloud computing [3]. Therefore, cloud computing is inadequate for a broad range of egressing mobile applications. It is necessary that the data processing of an application can take place at a geographically distributed data centers. This conducted to the egression of novel research arena called fog computing and networking [4], [5].

Mobility is an intrinsical trait of several fog applications to improve the experience of users. The users' movement and trajectories are providing location and personal preference information for the fog servers to ameliorate the effectiveness of conducting users' computation requests. Thus, mobility also poses a number of challenges in fog computing such as users' preferences, users' prediction, time limitation, geographical distribution, and distance constraints. Recently, researchers studied mobility phenomena in fog computing [6], [7]. However, it is based on the same conventional mobility proposals by considering connection probability or the link reliability according to users' speed and location. In addition, mobility had also been purposed to accomplish high data rate and low bit error rate. However, these works cannot be immediately employed for fog computing in dynamic environment [8], [9].

Fog computing has unique features such as security, cognition, agility, low latency, and efficiency. Despite these features, the end-user devices and fog nodes can be mobile and fog system should be adequate to handle the mobility management. In mobility, the interactions between users and fog nodes are not static, but are ergodic by nature. Thus, it becomes extremely opportunistic contacts due to the prospective mobility of interacted users. Owing the advantage of short distance between end-users and fog computing, it facilities efficient link continuity with relevant proximal devices for data computing. In contrast, the connection between fog server and end-users can be in a way that one or both users can be a mobile. Additionally, it is also possible that users can move in any or the same direction; serve in the same location while promising the continuity of connection. Therefore, mobility of users bring various important facets such as, increased outage probability, data failure transmission, offloading failure transmission, computation failure mechanisms, higher latency and increased overhead. Moreover, it is also important to bring the system wide performance on the frequent and opportunistic contacts in response to realistic user movement [10]–[12].

A. PRELIMINARIES

Fog computing was initially introduced by Cisco to extend the cloud computing to the network edge [13]. The OpenFog Consortium is founded by Advanced RISC (Reduced Instruction Set Computer) Machine (now ARM), Cisco, Dell, Intel, Microsoft Corporation, and the Princeton University Edge Laboratory. Initially, the objectives are to provide the standardization of fog computing in various field during November, 2015 [14]. OpenFog released the Reference Architecture (RA) for fog computing on the February 13, 2017 [14]. The most recent release of OpenFog Consortium is constructing an open architecture for fog computing to alter inter-operability and scalability. Several companies such as Cloudlet [15] and Intelligent Edge by Intel [16] are also supporting fog computing. Fog computing complements remote cloud and provides computing, storage, and networking services between the end user and cloud computing [8], [20], [32]. The architecture of fog computing [21]–[23] is shown in Fig. 1.

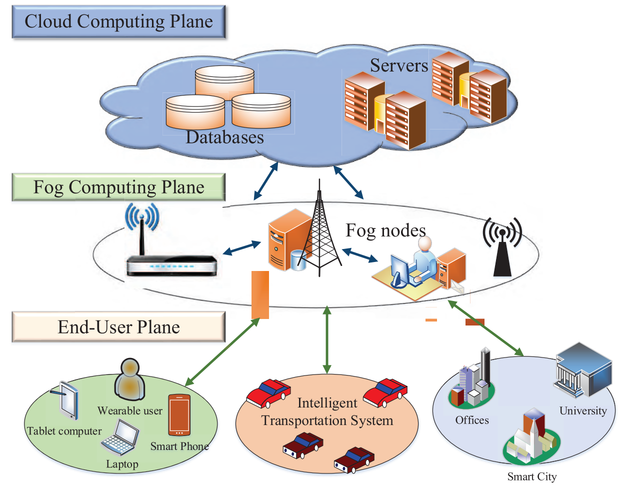

FIGURE 1. A comprehensive architecture of cloud computing, fog computing and end users platforms.

The fog computing conceptual model is proposed by the recent report of NIST on fog computing for the internet of things devices [24], [25]. The Internet of Things (IoTs) comprises smart and inter-connected devices which are utilized by the growing number of users and organizations. This proliferation is powered by smart sensors used to wireless smart sensors, fitness trackers for health, self-driving automobiles, and electric power grid stations. All of these products are stimulating and retrieving an increasing volume of data that desires to be retrieved more rapidly and locally. For this purpose, the cloud computing is responsible for managing and storing this huge amount of data. As we know, that cloud computing is centralized networks of servers and computers, whom are inter-connected together over the internet. However, such data requires intolerable time to access through the cloud and it can be slow at desirable time. The reason is the data requires to be transported to the cloud for storage, analysis and processing.

To decrease the amount of times for processing, an alternate to cloud computing is fog computing, which is a decentralized infrastructure. In fog computing, the data is accessed locally and considerably decreases the time it takes to access the data. Other alternatives such as mist computing, cloudlets, and edge computing have also been developed, along with the advent of fog computing. However, no agreement survives on the excellence among these notions. Thus, NIST proposed a conceptual model for fog computing that presents the conceptual models of fog and mist computing, and the relation towards cloud based computing models for IoTs [25]. The NIST report not only delivers the conceptual models of fog computing, and its subsidiary mist computing, but it also familiarizes the idea of a fog node, and the nodes coalition model. This is comprised of both distributed and centralized clusters of fog nodes operating in synchronization. The report is envisioned to assist as a means for comprehensive comparisons of fog computing abilities, service models, and implementation approaches, and to offer a benchmark for conversation of how fog computing works and how to utilize it. In contrast, it is also necessary to distinguish between cloud and fog computing, and fog and edge computing.

1) CLOUD VS FOG COMPUTING

Cloud service providers maintain data centers utilizing general purpose processors based cloud servers, and physical distances between cloud servers and end users are usually very long. Therefore, it suffers from substantial end-to-end delay, traffic congestion, processing of a huge amount of data, and communication cost. On the other hand, fog computing appears as an alternate to cloud computing, which is characterized as geographically distributed to ensure latency, QoS demands of data intensive and delay sensitive applications. Fog computing is an end-to-end horizontal architecture that facilitates a significant proportion of data storage, computing, communication and networking of cloud computing near to the end devices as depicted in the Fig. 2. It improves the overall system efficiency due to close integration with the end devices. A key difference between cloud computing and fog computing lies in the fact that the former optimizes resource in a global view, while the later systematizes and manages the local virtual clusters [8], [26]–[30], [32].

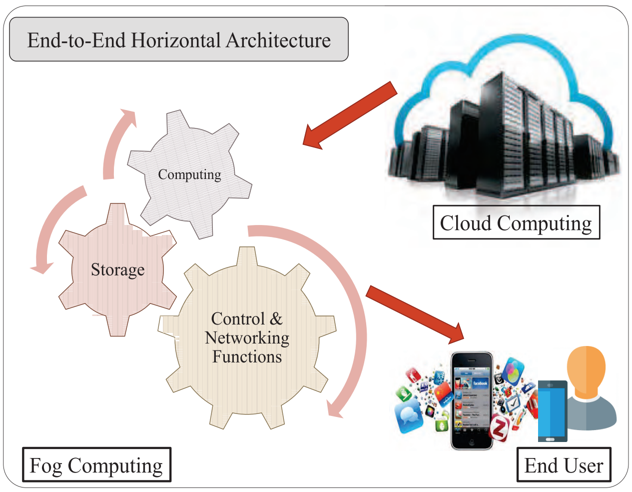

FIGURE 2. **End-to-End horizontal architecture of fog computing. Fog computing performs computing, storage, control & networking functions.**

2) EDGE VS FOG COMPUTING

Mobile edge computing standardization attempt commenced under the aegis of the European Telecommunications Standards Institute (ETSI) [31]. The Open Edge Computing initiatory was set up in June 2015 by certain companies such as Vodafone, Intel, and Huawei in partnership with Carnegie Mellon University (CMU) and flourished a year later to admit Verizon, Deutsche Telekom, T-Mobile, Nokia, and Crown Castle. This collaborationism holds creation of a Living Edge Lab in Pittsburgh, Pennsylvania, to achieve hands-on experience with a live deployment of proof-of-concept cloud-let based applications [17], [18].

The areas of fog computing and edge computing are imbrication, and the nomenclatures are often utilized interchangeably. The aims of fog computing and edge computing are interchangeable in terms of reducing end-to-end delay and lowering network congestion but the main difference is about the computation power. The difference is how to litigate and compute the data, and the placement of intelligence and computation power [33], [34]. A general utilization of the terminology pertains to the edge network as contradicted to the core network, with equipment such as edge routers, base stations, and home gateways. Thus, there are some differences between fog and edge. On the other side, fog is inclusive of cloud, core, metro, edge, clients, and things [18], [35]–[38]. The fog architecture will further enable pooling, orchestrating, managing, and securing the resources and functions distributed in the cloud. It support end-to-end services and applications anywhere along the cloud-to-thing continuum, and on the things [39], [40]. In addition, fog tries to recognize an unseamed continuum of computing services from the cloud to the things instead of dealing the network edges as obscured computing platforms [8], [32], [41]–[43].

B. MOTIVATION

Focusing on different aspects of fog computing, few research works have studied mobility factors to evaluate the performance of network dynamics in the real life scenarios. Researchers have also collected real-life vehicular and human mobility traces to understand the influence of the users' mobility in real life scenarios. In addition, although there exist several interesting surveys on fog computing which have brought considerable contributions and understanding related to fog computing, yet the important area of mobility research is still in progress. Therefore, a comprehensive and comparative study is lacking in the field of mobility-constrained or mobility-aware fog computing. A deep understanding of users' mobility, including human and vehicular mobility, will provide vital insights on mobility-aware fog computing. This motivates us to carry out a comprehensive survey and tutorial to study the impacts of users' mobility on the achievable performance of fog computing.

In this regard, this discussion is divided into five sections. After the introduction of fog computing in this Section I, we describe the basic concept of fog computing mobility in Section II. We also evaluate the diverse mobility factors to investigate the correlation between dynamic nodes with fog nodes, experimentally in Section III. We determine that the similarity between these dynamic nodes' correlatives with their propinquity fog nodes in fog computing. In addition, we also discourse the open disputes and futurity in fog computing due to mobility constraints in Section IV. Finally, our work is concluded in Section V.

II. MOBILITY IN FOG COMPUTING

In this section, we have investigated the basic concept of mobility in fog computing and its related problems, accordingly. The section is categorized into three parts, i.e., overview, low dynamic environment, and high dynamic environment. The overview portion is the building block of mobility in fog computing, in which we have discussed the scheduling mechanism and mobility management. The scheduling mechanism is an important part due to which we should extremely care in mobility aspect to provide quality of service (QoS). We explain the importance and related problems in the mobility management in fog computing. The next parts are about low dynamic environment and the high dynamic environment. These parts are mainly concerned about the human mobility and vehicular fog computing in order to provide more details for readers and researchers.

A. OVERVIEW

The mobility is investigated in the fog area for dynamic big data driven, and real-time urban surveillance chore of continuous target tracking to improve the system awareness. However, several works done are focusing on the optimization of mobility aware server selection, and do not pay attention at mobile devices and scheduling policies at fog computing data centers. It is necessary to focus the computation technique at both levels i.e., mobile devices and scheduling at fog computing to attain better QoE and network benefit. Therefore, we present two basic requirements, i.e., scheduling mechanism and mobility management for improving the QoE, QoS and reducing latency in fog computing.

1) SCHEDULING MECHANISM

Fog computing provides reduced latency and cooperation in annulling or lessening traffic over-crowding in the core network. Nevertheless, this might be more complex to handle each end-user's computation priorities, quality of service and prioritization of low delay applications. In the traditional scheduling mechanism, the fog computing server is to render the offloading priority order towards the end-users. It relies on the users' different local computing data, channel gains and latency demands. In case of multiusers fog computing systems, the static scheduling strategy cannot be directly utilized with mobility because of dynamic environments [44]–[46]. This includes time varying channels and sporadic connectivity. Therefore, the scheduling mechanism become more challenging with the advent of dynamic environments. For instance, what, when, and where the end-users will accomplish processing requests to achieve their QoS and latency requirements. In addition, scheduling mechanisms must integrate mobility of data sources and sinks in the fog computing with smart and wearable devices. It is necessary that scheduling should contribute users location to the resource allocation policies to preserve the profits of fog computing proximity to the end-users. In the view of this discussion, the dynamic environment motivates us to design the adaptive server scheduling that reclaims the scheduling order from time to time and incorporates the real time users' information. The users with worst condition will be allocated with higher offloading antecedences to attain their computing deadlines via adaptive scheduling mechanisms. The mobility aware offloading priority design is also presented in [47]. The approach is utilized to precisely anticipate users' mobility profiles and channels. It will help overcome the effect of mobility and re-determine the offloading antecedence function. Secondly, it is resource reservation strategy that can improve the server scheduling functioning [48]–[50].

Furthermore, mobility management along with traffic control is presented in [51] to offer better users' QoE with latency tolerant tasks. This is designed with help of intelligent cell association procedure. For edge caching, the mobility predication is integrated to improve the content caches migration located at the edges [52]. Caching on the edge is also discerned as an effectual contribution to harness the backhual constraint of network concretion. For further compromising and context-aware caching determination, the conception of caching on the edge can be covered to mobile edge computing (MEC) [53]–[56]. It enables computation and storage resources at mobile edge networks. A vast quantity of collected radio access network context data can be examined and applied to deliver an adaptive caching scheme to user's context-aware information with MEC servers [57].

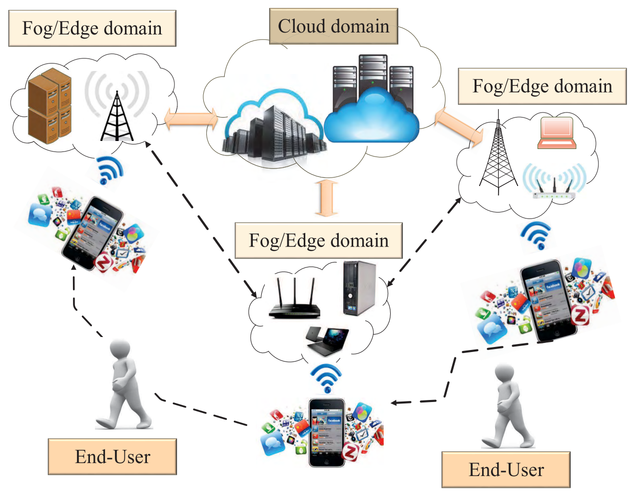

FIGURE 3. Mobility of end-users in fog/edge computing scheduling mechanism & mobility management.

2) MOBILITY MANAGEMENT

Fog computing servers can reserve some dedicated computational resources for mobile users to deliver consistent computing service and guarantee QoS for latency sensitive users [58]. For instance, the end-user is watching a video content and roams from a source fog-enabled access point (AP) to the destination fog-enabled access point. The fog system needs to be adequate to offer the end-user with the same video content from where it is left without disrupting the service such as illustrated in Fig. 3. For this purpose, architectural modules, like mobility facets are required to guarantee the mobility management for end-users [32]. The mobility can execute diverse decisions via mobility handling algorithms. For example, there are various end-users watching the same video and roaming in different directions, the mobility dealing algorithm might necessitate the mobility facets to replicate the video and drive a copy to the terminus fog-enabled AP. On other hand, resource deracination happens along with the significance on resource management algorithms for the case of fog nodes' mobility [32].

On the other side, latency tolerant users can get on demand provisions from edge servers. This hybrid server requirement can optimize the server scheduling for delivering the uttermost users with good QoS along with the servers' revenue maximization. However, computation offloading in fog computing may be failed due to sporadic links or/and rapid varying in wireless channels. The failure is disastrous for both the latency sensitive and resource requiring applications. These issues are discussed in [59] and [60], and evidenced that it is necessary to design mobility-aware fault tolerant such as fault prevention, fault detection, and fault recovery for fog computing systems.

3) SUMMARY

The fog computing scheduling and mobility management must be able to generate the scheduling order of dynamic users from time to time, geographical area, and to integrate the real life scenario of users' information. However, it is also necessary to predict the users' profiles and their daily routine to effectively improve scheduling performance as well as mobility management. However, as per the authors' knowledge, none of the existing research works till date presents the true nature of a dynamic environment in fog computing scheduling. Therefore, mobility information of users are necessary to predict the users mobility profiles and channels. This will help the users to improve their QoE and offloading capabilities according to their geographical locations. In the eye of state-of-the-art research, we divide the mobility of fog computing into two basic categories: low dynamic environment and high dynamic environment.

B. LOW DYNAMIC ENVIRONMENT

Device-to-device (D2D) communications underlying cellular networks, utilizing the same spectrum as cellular user (CU), is considered as a novel epitome with prominent potential for affirming the proximity-based applications [61]–[63]. Taking the advantage of D2D communication, D2D fogging is also become a new paradigm in mobile task offloading framework. Here, mobile users are in low dynamic environment and can beneficially contribute the computation and communication resources among each other through the base station (BS). In addition, the capabilities of mobile device are constantly improving and the multiplexing gain can be leveraged to endorse cooperative task performance for diverse applications. Nevertheless, D2D fogging faces challenges due to time varying cellular posits and usable D2D connections. The time varying cellular posits and stochastic and unpredictable D2D connections are due to users' mobility and device computational resources [64]. Moreover, task offloading framework should provide better attempt to accomplish network broad optimal energy conservation for users' task performance. Last but not the least, the D2D fogging model needs to furnish an adequate incentive method. It powerfully conceives on user collaboration and thus, a better incentive method can preclude the over exploitation that harms user's motive for collaboration.

In these regards, Pu *et al.* [64] proposed an optimization formulation that aspires at minimizing the time average and energy consumption of task execution. The authors proposed the Lyapunov optimization methods to overwhelm the dispute of future information prediction of users' resource availability due to mobility. Chen and Zhang [65] proposed HyFog, a hybrid task offloading model in fog computing. Here, end-users have the tractability of preferring among various alternatives for task executions, including mobile execution, D2D offloaded execution, and cloud offloaded execution. For this purpose, the authors designed three layer graphs to investigate the option of space enabled by these three execution approaches. Nonetheless, the mobility is not fully integrated in those works. The users' mobility or fog node mobility is not fully characterized in these works.

D2D fogging must also be utilized to deal the user mobility in fog computing system to create various D2D links [66]. These links permit the computation of a user to be offloaded to its proximity users. This creates an effective computation potentialities and reduces energy consumption of data transmission. This allows us to research on users mobility to brings new design issues in fog/edge computing. For instance, to leverage the vantages of both D2D and cellular communications, the potential method is to offload the computation intense data to the edge servers at the BSs that have immense computation potentialities in order to lessen the server-computing time [67].

SUMMARY

The constituent of huge data sizes and stringent computation demands might be conveyed to the proximate users through D2D communication for more prominent energy efficiency [68]–[70]. The option of nearby users for offloading must also be optimized to account for users' mobility information, dynamic channels, and heterogeneous users' computation capacities. However, massive D2D links will also bring in austere disturbance for reliable communication. This subject is more complex in mobility based edge systems because of rapid variations in wireless evanescing environments. Thus, interference cancellation and cognitive radio methods can be useful for fog/edge computing system along with the mobility anticipation to enhance the offloading rate and decrements the service response time.

C. HIGH DYNAMIC ENVIRONMENT

Vehicular fog computing (VFC) consists of three layers of entities, i.e., vehicles as the data generation layer, road-side units (RSUs) as fog nodes and cloud servers as cloud layer, and are considered in high dynamic environments as depicted in Fig. 4. VFC networks are familiar as a substantial component of the future intelligent transportation

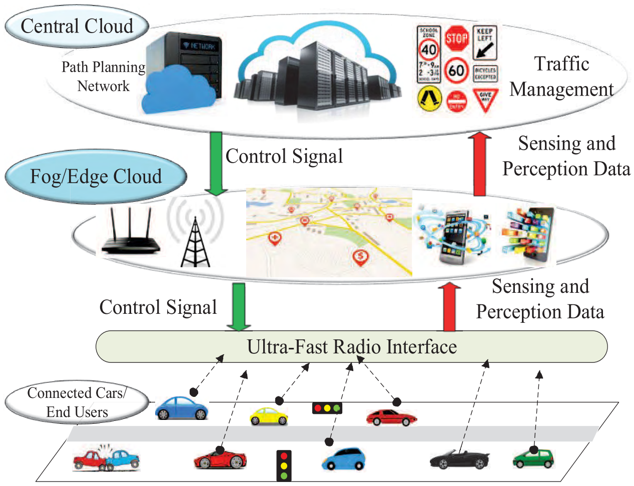

FIGURE 4. Mobility scenario of vehicular fog computing.

system (ITS) [71]–[73]. They support numerous mobile services such as advertisements, entertainments, and emergency operations for natural disasters [74]–[76]. VFC ensures driving safety, traffic efficacy and significant convenience by commuting valuable information. Since the last decade, VFC networks and related applications have been developed extensively with the advent of more advance devices and technologies, i.e., cellular networks and cloud computing. Apart from opportunities some serious challenges also appeared, which include the drastic increase in the requirement of data communication and computational capacity. Novel applications, such as augmented reality (AR) technics [77], self-driving are dealing with composite data processing and storing processes. It requires a higher level of data communication, computation, and storage, which incline to eminent challenges to the prevailing conventional vehicular networks. Therefore, VFC as data centers and improved processing resources is attracting notion to conform to this ever-increasing requirement in data communication and computational capabilities. The VFC is taken under consideration due to the high speed of moving vehicles. However, there may be two scenarios involved in vehicular fog computing, e.g., parked and moving vehicles service and applications [78].

1) PARKED VEHICLES

Most of the vehicles are parked along the road or in the parking area during daytime and over night time for a couple of hours. Thus, parked vehicles along the road sides can play an important role in relaying data. On the other side, vehicles in the parking area can create a computation fog. Hence, the capacities of the area can be ameliorated in terms of communication and computational tasks. Parked vehicles are distributed geographically in street parking, outdoor parking and indoor parking. These parked vehicles have certainly comparatively unaltered positions over a certain time period. Therefore, it cannot convey the data from one place to another place. However, parked vehicles can easily communicate with other parked or moving vehicles. These parked vehicles join together and collaborate with each other under suitable communication condition to attain large computing tasks. Therefore, it provides a lot of computation resources and become abundant computation infrastructures. However, individual vehicles bear specified computation resources [79]. This computation capability issue can be figured out by VFC. VFC provides powerful computation resources and accomplish computing tasks in less time and efficiently. For example, when the parked vehicles join VFC in the parking area, the vehicles form a small data center, and consequently, can conduct various complicated tasks that demand high computation ability. In addition, a moving car can also get advantages from VFC. For instance, a passing by car need to deal with some complex task or need some resources, and they can join the parking VFC for a couple of time till by completing their job.

Another simple example is the vehicular parking lot at a company for establishing vehicular clouds, which can be used to deal the computational tasks or it can be utilized to cooperate with each other to transmit data and share-out communication resources [78]. The conventional solutions for communication and computational support such as cellular networks, Road Side Units (RSUs), and mobile cloud computing (MCC) are far from the perfect due to powerful communication as well as higher computational support. In addition, it also requires the cost of additional infrastructure deployment. Keeping this in view, Hou *et al.* [79] proposed the notion of exploiting vehicles as infrastructures for communication and computation in VFC. The authors utilized the architecture to collaborate between the multitude of end user (vehicles) or near edge devices (APs), in order to perform the communication and computation resources of each vehicle. The architecture of VFC also reveals the correlation among the communication potentiality, connectivity and mobility of vehicles, and the pattern of parking behavior.

2) MOVING VEHICLES

The communication and computation between vehicles can be carried out with the combination of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). As for V2V, direct communication and computational can be problematic due to distance and speed between the vehicles. Thus, the network connectivity is the major problem for enabling information transmission between V2V communication. Hence, VFC utilizes moving vehicles as communication infrastructure to bring better network connectivity between vehicles. VFC can take the vantages of multi-hop characteristics and moving characteristics of vehicles to convey the information from one place to another.

Moving vehicles in close geographic positions can collaborate and associate with each other due to the coveted features of VFC, e.g., geo-distribution and local decision making. Particularly, vehicles can act as a communication hubs by connecting the near located vehicles together, and thus connecting with more mobile APs. The fog is formed due to these communication hubs and tasks can be completed by employing computational and communication resources locally rather than delivering the information to the cloud servers. The communication and computational resources contains both local decision making information and geo-distribution characteristics, which brings low delay and cost, and high efficiency. In a recent article, Sookhak *et al.* [80] also presented the architecture of VFC. The problem to alleviate the resource restrictions of fog computing is depicted, in which several unused resources of vehicles can be provided to improve fog computing resources. The authors illustrated the cross-layer structure of VFC, and explicated the constituent elements along with their purpose in the construction of VFC. The architecture also explained a decision making process and presented diverse cases of services; those are assigned among vehicles.

3) SUMMARY

The vehicular networks consist of thousands of vehicles which are moving from one place to another place. They seek to link each other as long as the communication consideration is countenanced. In order to implement VFC, we require to contrive efficient protocols, and associated management techniques to communicate with proximate moving or parked vehicles. With respect, we need a suitable and precise mobility model that is indispensable to expect and measure the movement of neighboring vehicles in order to offer overt understanding of communication circumstances. Thus, to design a VFC system, we need an appropriate mobility model for vehicles. The existing mobility models are insufficient and imprecise for the vehicular moving process in VFC. As a result, we need significant information about the precise behaviors of the vehicles such as, speeds and distributions in both response time and space domains in order to implement in fog computing. With the knowledge of response time and space domain, we can explore the familiarity between the connectivity and mobility of vehicular networks.

III. EXPERIMENTAL EVALUATION

This section describes the simulation of different interactions between mobile nodes and fog nodes to investigate the mobility information and predict the contact between mobile end-user and fog server. These mobility information are captured by the level of proximity between mobile and fog nodes. It is obvious that people who share frequent interactions are supposed to have an improved likeliness of creating new connections. Consequently, our investigation is based on three basic measurements, which aims to determine the likeliness of mobile nodes with fog nodes in a certain geographical area.

A. PRELIMINARIES

We consider users as dynamic nodes, and are labeled as $\mathcal{N} = \{n_1, n_2, ...n_{\mathcal{N}}\}$ and fog nodes are denoted as $\mathcal{F} = \{f_1, f_2, ..., f_{\mathcal{F}}\}$. These mobile nodes are considered as users with wireless mobile devices, and their locations varies with respect to time and space. However, the fog nodes are assumed to be constant during interactions with mobile nodes. Moreover, the interactions between mobile node $\mathcal{N}_i$, $\forall i \in \mathcal{N}$, and fog node $\mathcal{F}_j$, $\forall j \in \mathcal{F}$ are based on inter-contact time, contact rate, and contact duration which is defined as the following definitions [83], [84].

Definition 1 (Inter-Contact Time): The inter-contact time between users $\mathcal{N}_i$ and $\mathcal{F}_j$ is outlined as *"the time taken to meet within the range of each other again from the last time (t_0), to the time that they are traveling out of the range to each other"*, which is denoted by $\mathcal{I}_{i,j}$ and given as,

$$\mathcal{I}_{i,j} = \min_{t} \left\{ (t - t_0) : \left\| L_i(t) - L_j(t) \right\| \leq R_{i,j} \right\}. \tag{1}$$

For $t > t_0$ and $L_i > 0$ & $L_j > 0$, and $L_i(t)$ and $L_j(t)$ are the positions (locations) of users $\mathcal{F}_j$ and $\mathcal{N}_i$ at time t, accordingly, $R_{i,j}$ refers the transmission scope between $\mathcal{F}_j$ and $\mathcal{N}_i$, and $\|\cdot\|$ relates the distance calculated between the corresponding fog nodes and end-users.

Definition 2 (Contact Rate): $\lambda\!\!\!-_i$ relates the contact rate of $\mathcal{F}_i$ and $\mathcal{N}_j$, and is defined as [81]: $\lambda\!\!\!-_i = \frac{1}{E[\mathcal{I}]}$, where $E[\cdot]$ is the expectation operator.

Definition 3 (Contact Duration): It is determined as, the nodes $\mathcal{F}_j$ and $\mathcal{N}_i$ come in contact at time t_c, i.e., $\left\| L_i\left(t_c^-\right) - L_j\left(t_c^-\right) \right\| > R_{i,j}$ and $\left\| L_i\left(t_c^-\right) - L_j\left(t_c^-\right) \right\| = R_{i,j}$, where t_c^- is the time before t_c. The contact duration between nodes $\mathcal{F}_j$ and $\mathcal{N}_i$ is set as the time during which they are in contact before moving out of the communication range, i.e., $\mathcal{I}_{i,j} = t - t_c$ with $\min_{t-t_c} \left\{ t : \left\| L_i(t) - L_j(t) \right\| > R_{i,j} \right\}$, where t and t_c are at continuous time scale.

The mobility information is to look the level of proximity in physical space between nodes. In order to predict the connection between $\mathcal{F}_j$ and $\mathcal{N}_i$ focused on specifying an effective network based proximity measures (also it is the characteristic of fog computing). The proximity nodes that are close enough to make connection in the present may also have better likelihood of becoming connected in the future. However, according to the basic concept defined in [82], which states that those nodes that share high level of overlapping in their trajectories are predicted to carry out better performance. Nevertheless, the performance of the two connected or connecting nodes are calculated on the completion of tasks of $\mathcal{N}_i$ with $\mathcal{F}_j$.

We assume that mobile nodes $\mathcal{N}_i$ will only communicate with fog nodes $\mathcal{F}_j$ when they are moving within the transmission range of each other, which is termed as contact rate. The contact between $\mathcal{F}_j$ and $\mathcal{N}_i$ is calculated for the first time then the amount of task is generated and the amount of computation will be offloaded. In addition, the updated task must be done at any time before the deadline. When all the tasks are fulfilled before the total time duration, we may say that the tasks are successfully accomplished. Hence, the performance is based on task completion between $\mathcal{F}_j$ and $\mathcal{N}_i$, and is measured in term of the success ratio that is defined as follows.

Definition 4 (Success Ratio): It is referred as $\mathcal{X}_i$, and is outlined as $\mathcal{X}_i = x_1/x_2$, where x_1 is the number of successful tasks and x_2 is the total number of tasks during certain period of time.

B. MOBILITY FACTORS

The mobility factors quantify the measurements that capture the level of physical proximity between $\mathcal{F}_j$ and $\mathcal{N}_i$ [83], [84]. In result, our simulation is considered on a series of quantities directing to define the similarity in mobility patterns of mobile users. It interprets the physical distance between $\mathcal{F}_j$ and $\mathcal{N}_i$ about their most often positions. Let $L(i) = \text{argmax } P_r(i, l)$ be the most probable positions of user i i.e., $P_r(i, l) = \sum_{i=1}^{\mathcal{N}} \sigma(l, L(i))/n(i)$ is the probability in which users visit the location most frequently. Therefore, it is important to define the basic mobility factors in our daily routine. Hence, the mobility factors are defined as following.

Definition 5 (Same Encounters): These interactions or encounters are named as ***same encounters*** due to the fact that $\mathcal{N}_i$ interact or meet with $\mathcal{F}_j$ at the same location during the same time span, i.e., time frame (1 hour). Hence, it may be defined as *"The probability in which the interactions appears at the same location during the same time duration"*. Mathematically, it can be written as:

$$P_1 \equiv \frac{\sum_{i=1}^{\mathcal{N}_i} \sum_{j=1}^{\mathcal{F}_j} \mathcal{H}\left(\Delta T - \left|T_i - T_j\right| \delta\left(L_i - L_j\right)\right)}{\sum_{i=1}^{\mathcal{N}_i} \sum_{j=1}^{\mathcal{F}_j} \mathcal{H}\left(\Delta T - \left|T_i - T_j\right|\right)}, \quad (2)$$

where $\mathcal{H}$ is the Heaviside step function. This measurement takes into consideration the simultaneous imposes of the two mobile users at the similar location, i.e., both are in spatial and temporal proximity. It is normalized by the number of times that the users are determined at the similar time frame.

Definition 6 (Partly Encounters): These interactions or encounters are named as ***partly encounters*** due to the fact that $\mathcal{N}_i$ interact or meet with $\mathcal{F}_j$ at the same location during different time span. Hence, it is described as *"the probability that users visit at the same location during different time"*, and it is written as:

$$P_2 \equiv \sum_{i=1}^{\mathcal{N}_i} P\left(\mathcal{N}_i, l\right) \times \sum_{j=1}^{\mathcal{F}_i} P\left(\mathcal{F}_j, l\right). \quad (3)$$

Definition 7 (Different Encounters): We also compare the probability of ***different encounters***, where user trajectories are captured by their visiting frequencies irrespective of time and location. It is assigned by the cosine of the angle between two vectors of the number of visits at each location. It can be written mathematically as:

$$P_3 \equiv \sum_{i=1,j=1}^{\mathcal{N}_i,\mathcal{F}_j} \frac{P\left(\mathcal{N}_i, l\right) \times P\left(\mathcal{F}_j, l\right)}{\left\|P\left(\mathcal{N}_i, l\right)\right\| \times \left\|P\left(\mathcal{F}_j, l\right), \right\|}. \quad (4)$$

C. EXPERIMENTAL EVALUATIONS

We investigate a series of connections between the similarity of fog nodes and mobile nodes by measuring their correlation. It is well-known that those who share a high level of imbrication in their trajectories are predicted to accomplish better success ratio. Therefore, we consider a natural strategy to predict the similarity of mobile nodes with fog nodes for successful tasks. As we mentioned in our previous discussion that the tasks are successfully accomplished when all the tasks are fulfilled before the total time period, and therefore, it necessitates to calculate the contact rate between the mobile nodes $\mathcal{N}_i$ and fog nodes $\mathcal{F}_j$. Otherwise, in a dynamic environment when mobile nodes do not find any fog nodes for computation or offloading, it may impact negatively. Hence, first we calculate the contact probability between them. Second, we investigate the effect of mobile users and fog nodes in the network, and see the performance evaluation of different mobility factors. Finally, the important factor is the time duration for mobile nodes $\mathcal{N}_i$ to complete their tasks within their certain duration of time in dynamic environments.

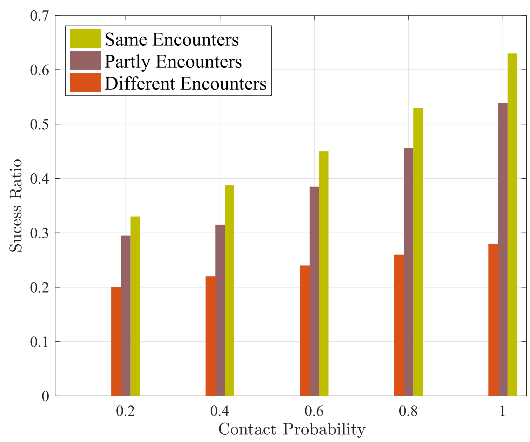

FIGURE 5. Success ratio versus contact probability of dynamic nodes $\mathcal{N}_i$ by measuring *same encounters, partly encounters and different encounters* with static fog nodes $\mathcal{F}_j$.

1) SUCCESS RATIO VERSUS CONTACT PROBABILITY

According to the definitions in our previous discussion, we calculate the three mobility factors for contact probability. We are also interested to measure contact probability of those nodes which meet at the same time during the same time period (***same encounters***), same location during different time period (***partly encounters***), and finally random behavior of nodes (***different encounters***). For this purpose, we consider 100 nodes in total in which 10 nodes are considered as fog nodes while the other 90 are mobile nodes. It is observed from Fig 5, that nodes having connection at the same time during the same time period are 25% and 7% higher than the ***partly encounters*** and ***different encounters***, respectively. Hence, we can conclude that for dynamic environment, the contact probability of $\mathcal{N}_i$ are higher when they meet with the fog nodes $\mathcal{F}_j$ at the same time during the same period of time. After calculating the contact probability, our second step is to measure the success ratio with the effect of increasing the number of nodes.

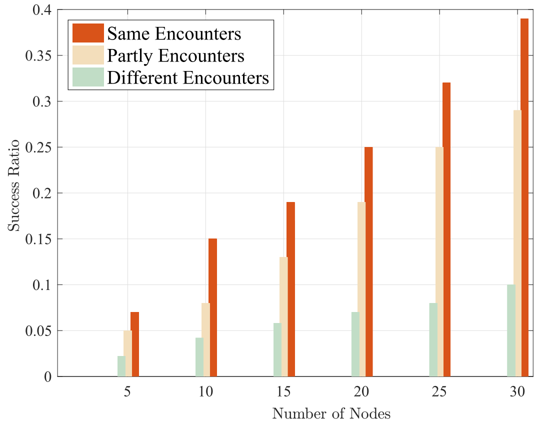

FIGURE 6. **Success ratio versus number of dynamic nodes $\mathcal{N}_i$ by measuring *same encounters, partly encounters and different encounters* with static fog nodes $\mathcal{F}_j$.**

2) SUCCESS RATIO VERSUS NUMBER OF NODES

Fig. 6 depicts the successful ratio against the number of devices. In this experiment, the dynamic nodes $\mathcal{N}_i$ and fog nodes $\mathcal{F}_j$ are uniformly increasing. For instance, among 20 nodes, 10 nodes are considered as fog nodes while the other 10 are considered as dynamic nodes $\mathcal{N}_i$. Initially, the success ratio increments with the increase of the number of nodes for all three mobility factors. Nevertheless, when the number of nodes increases, the content success ratio rapidly increases. The reason is that dynamic nodes have more chances to meet with a higher number of fog nodes in a dynamic environment. However, the success ratio is varying for diverse encounters. Comparatively, the success ratio due to users' mobility based on the ***same encounters*** is higher than ***partly encounter*** and ***different encounters***, respectively. For instance, ***same encounters*** are almost 9% and 28% greater than ***partly encounters*** and ***different encounters***, respectively, when the number of nodes are 30 (15 fog nodes & 15 dynamic nodes). As a matter of fact, the probability of users to meet at the same location and time is higher than those users who appear at the same location but different time.

3) SUCCESS RATIO VERSUS TIME COMPLETION

We compare the simulations of the ***same encounters***, ***partly encounters***, and ***different encounters*** for success ratio with time variation in Fig. 7. In this experiment, we limit our fog nodes to 10, and keep the dynamics nodes 50. From Fig. 7, we discover that the nodes accomplish a higher success ratio, when the time limit raises. Moreover, it is observed that all the three encounters achieve almost the same success ratio. However, ***different encounters*** achieve 6% better performance than ***partly encounters***, and 8% better than ***same encounters***, respectively at 10 sec. It is also revealed

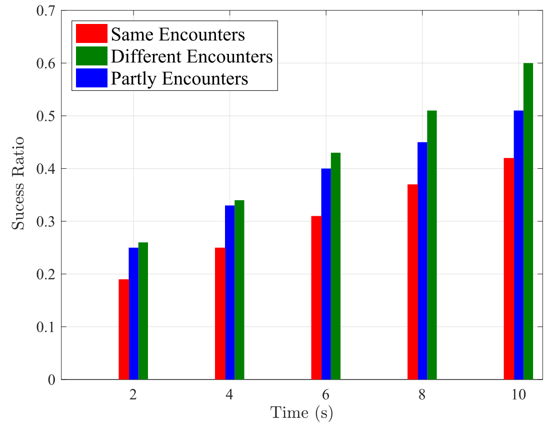

FIGURE 7. **Success ratio versus of time duration of dynamic nodes $\mathcal{N}_i$ by measuring *same encounters, partly encounters and different encounters* with static fog nodes $\mathcal{F}_j$.**

that ***partly encounters*** performs 2% better than the ***same encounters*** at 10 sec. Although, the contact probability of the ***same encounters*** and ***partly encounters*** are higher than the ***different encounters***, they are compelled by time and space, respectively. On the other hand, ***different encounters*** are without the constraint of time and space, which entails, it can achieve the success ratio higher at any time and space. Therefore, it achieves better performance. In simple words, dynamic nodes can encounters irrespective of time with static fog nodes. Therefore, ***different encounters*** achieve slightly higher performance than the ***same encounters***.

D. SUMMARY

The mobility encounters discussed in this work is a practical alternative applicant to anticipate the network structures, and encourage the exploration of a newly approach to expect the interaction between mobile nodes and fog nodes. It also serves as a beneficial representative for establishing new connections, yielding correspondent prognostic power to traditional network based measurements. However, the mobility measurements of nodes' interaction greatly depends on the mobility patterns. Because the higher intensity of users' interactions pointed out the higher mobility patterns between them.

IV. OPEN PROBLEMS

Based on the above overall discussion and experimental verification of mobility factors, we come up at the point to present some open problems for future directions. These open problems open a gateway for researcher to think about the practical implementation of users mobility in the fog computing. The open problems will help researchers to move in a new direction that concerns about the real life implementation. It is a solid case to cautiously evaluate the existing challenges, assessing out the best solutions, detailing the resulting advantages, and finding the best technological solutions. Therefore, we present the open problems that will merit future research directions.

A. USERS' MOBILITY MANAGEMENT

Mobility management is one of the basic requirements to minimize the negative impacts on fog computing [85]. Such negative impacts comprise of larger latency and additional signaling congestion in fog computing. Mobility management become crucial in fog computing and it requires proper algorithms to develop, which can deal it without interruption. Very few papers hashed out the mobility management in fog computing. However, proper investigations, and usage of proper algorithms are yet to be developed to handle such problems. An important factor in fog computing is latency. Hence, a low latency reliable fog computing between dynamic users and fog servers is a challenging chore that is yet to be explicated.

B. USERS' MOBILITY PREDICTION

Mobility prediction is an interesting research area which is established on recent history. Mobility expectancies and their comparability with empiric data might assist to realize human movement in a concise manner. It is influenced that we can recognize much about human mobility. Human beings are frequently invoked to popular locations, and the popularity of popular places importantly ascertains their frequency of visit to such areas. Such places can act as attraction points and people may repeatedly visit such places. It is believed that mobility patterns can be easily collected in such a kind of places.

C. GEOGRAPHICAL INFORMATION OF USERS AND NETWORK

It is also an interesting research direction to obtain data that contain the geographical and network information at the same time. None of the existing work indicates the strong correlation between geographical and network information that emerges in many diverse techniques. This kind of information represented the similarity between users' movements, and the effectiveness of interaction between them. Human mobility in their geographical location serve as a good prognosticator for the information. In addition, by aggregating both mobility and network measurements, we can find the prediction accuracy that can be significantly improved in the supervised acquisition. It is also necessary to investigate that the improvement of link prediction tasks from geographical location of the users and network measurements.

D. RESOURCE MANAGEMENT AND SCHEDULING STRATEGIES

The fog architecture is hierarchical and the decision on processing and storage location is subject to the application restraints and user geo-location. It could offer reduced latency and traffic congestion in the core network [4], [89], [90]. These mechanisms must integrate mobility of data sources and sinks into the fog. Fog computing scheduling should contribute users' location to the resource allocation strategies to maintain the gains of fog computing proximity to the users. Furthermore, user behavior governs the time and position of a computing device, along with QoS constraints. Therefore, prediction of mobility fails to achieve, if there is lack of information or unpredictable behavior of users. Therefore, scheduling in the context of mobility prediction failure is an interesting research problem that requires extensive research in fog computing. Scheduling models that capture mobility patterns can be developed and more effective resource management algorithms can be designed. Nonetheless, with efficient scheduling algorithms for fog computing, resource management arrangement still confronts challenges due to uncertainty engendered by the dynamicity and heterogeneity of the resources in fog computing.

E. SECURITY AND PRIVACY ISSUES

The fog nodes similar to end user can also join and leave the fog layer. Thus, it is a paramount requirement to assure the continuous service to the registered end users when a new fog node joins the fog layer due to mobility. The end users must be able to manifest themselves to the fog layer reciprocally [91]–[93]. The complications of registration and re-authentication phase are taken into account without huge overhead. However, the question arises that how to deal the security and privacy problems of mobile fog nodes? For instance, first, how mobile end user or mobile fog node can authenticate themselves and how end user protects their privacy due to the mobility of fog node. The second problem occurs about the low complexity based authentication between end users and fog nodes. Thus, mobility of fog node or end-user bring serious problems regarding security and privacy, which can open a gateway to many new research directions [94]–[98].

V. CONCLUSION

Mobility is an intrinsic trait of many fog and edge applications to improve the users' experience. As a matter of fact, mobility of end users and/or fog nodes brings a major dilemma in the implementation of real life scenario. Therefore, it is paramount to tackle different problems in fog computing due to the mobility. Our work furnishes detailed review and state-of-the-art researches in mobility, and its impact on fog computing. Due to recent progress and interest in fog computing, we elaborate the issues related to mobility in fog computing. We have also figured out the quantity that characterizes the proximity in dynamic environment by measuring the mobility factors.

In addition, we distinguish the open problems that merit future research directions in the last section. We believe that the discussion will suffice as a reference for researchers to facilitate the design and implementation of mobility-aware fog computing. This will help researchers distinguish open problems and move in new direction concerning the real life scenarios of people and vehicles in a dynamic fog computing environment.

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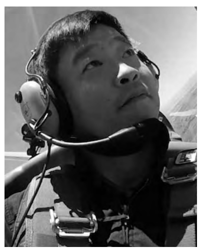

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